Present and future of Photovoltaic Solar Electricity

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Introduction

Crystalline silicon technology, from quartz to system

Economical and environmental issues

Alternatives to cristalline silicon technology

Conclusions

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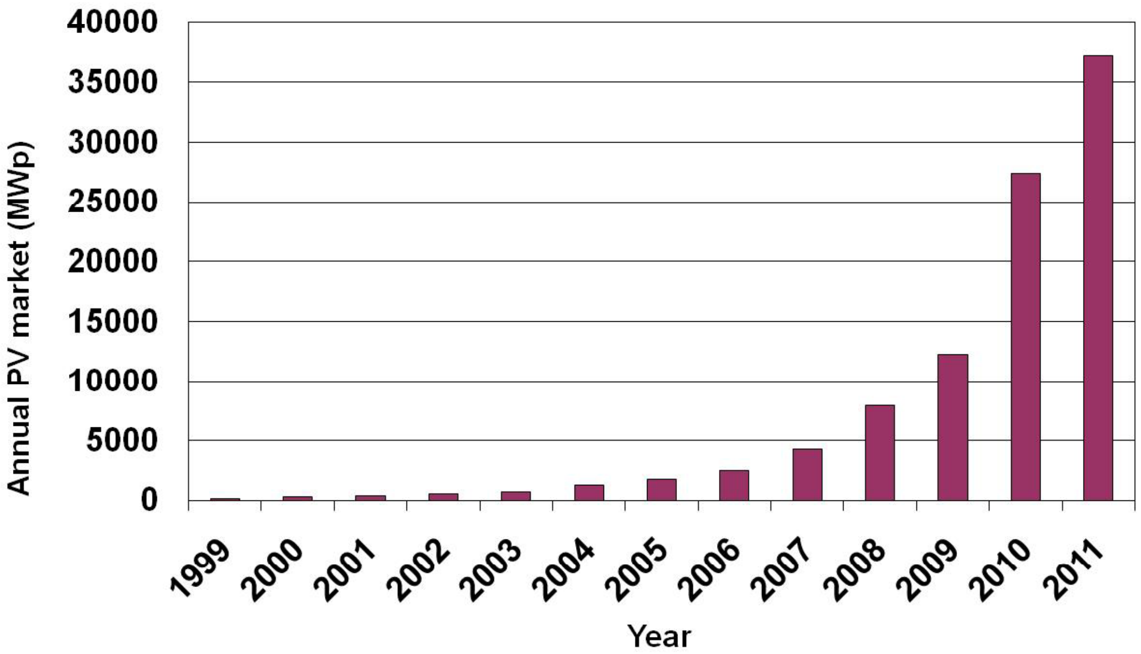
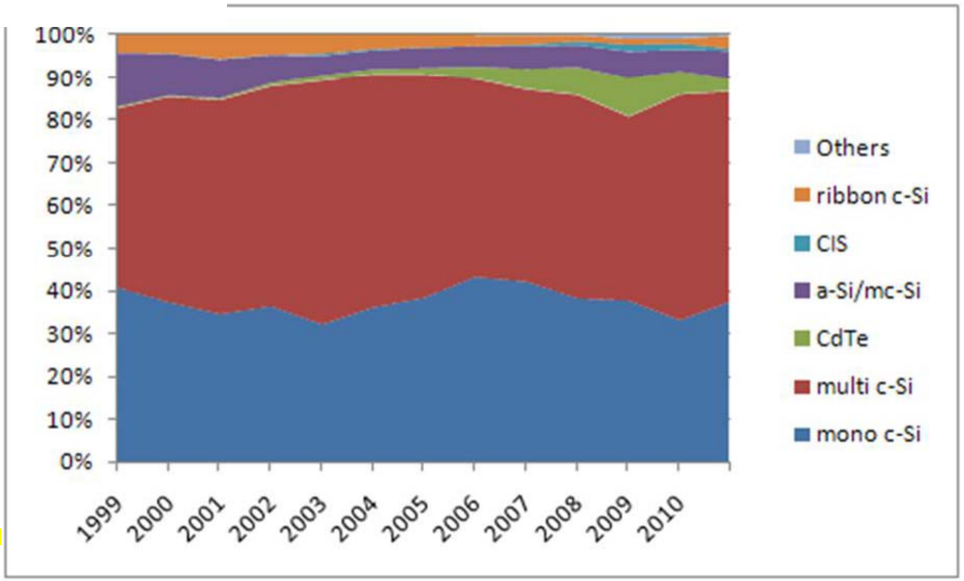
The photovoltaic (PV) industry



Continuous growth

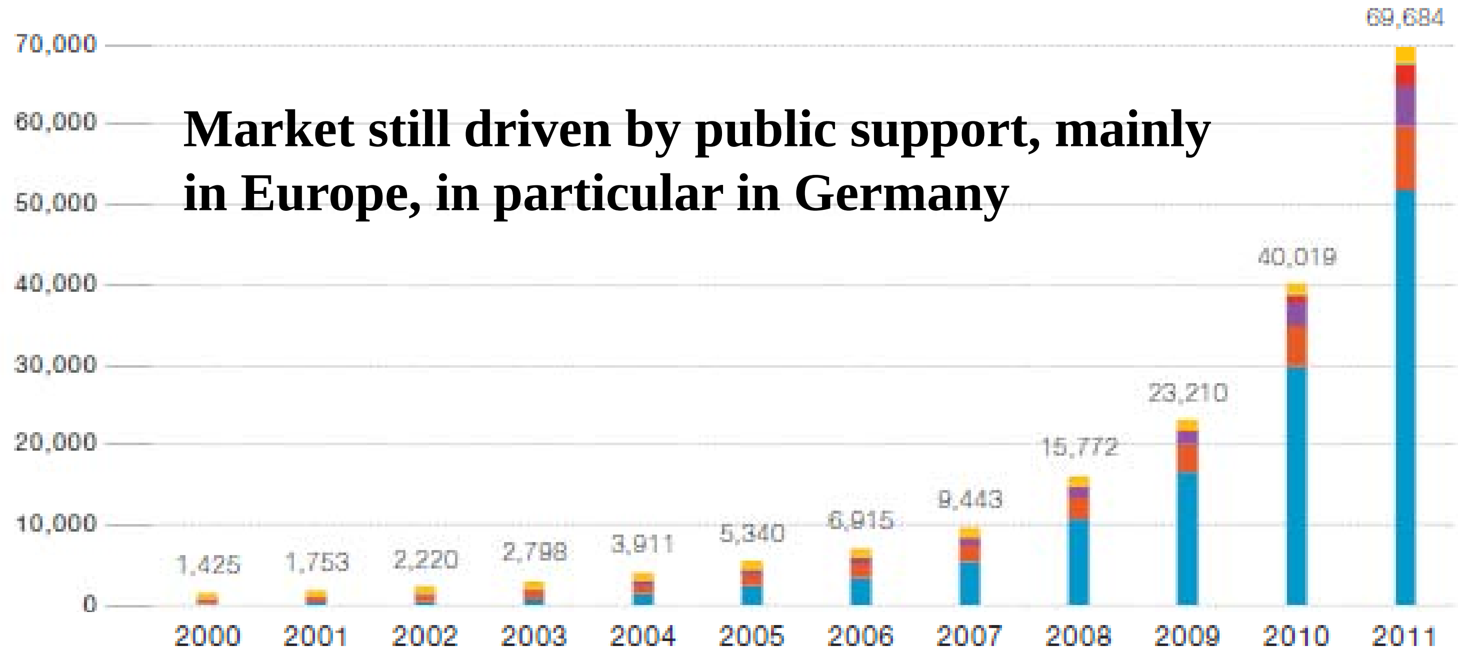
Crystalline technology still dominant, but the share of other technologies is growing



Photon International 3/2011

PV market distribution

· Evolution of global cumulative installed capacity 2000-2011 (MW)



Market still driven by public support, mainly in Europe, in particular in Germany

	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
ROW	751	807	887	964	993	1,003	1,108	1,150	1,226	1,306	1,209	1,717
MEA	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	21	205	336
China	19	30	45	55	64	68	80	100	145	373	893	3,093
America	146	177	222	287	379	496	645	856	1,205	1,744	2,820	5,053
APAC	355	491	677	902	1,178	1,475	1,797	2,080	2,643	3,409	5,116	7,769
Europe	154	248	389	590	1,297	2,299	3,285	5,257	10,554	16,357	29,777	51,716
Total	**1,425**	**1,753**	**2,220**	**2,798**	**3,911**	**5,340**	**6,915**	**9,443**	**15,772**	**23,210**	**40,019**	**69,684**

EPIA 2012

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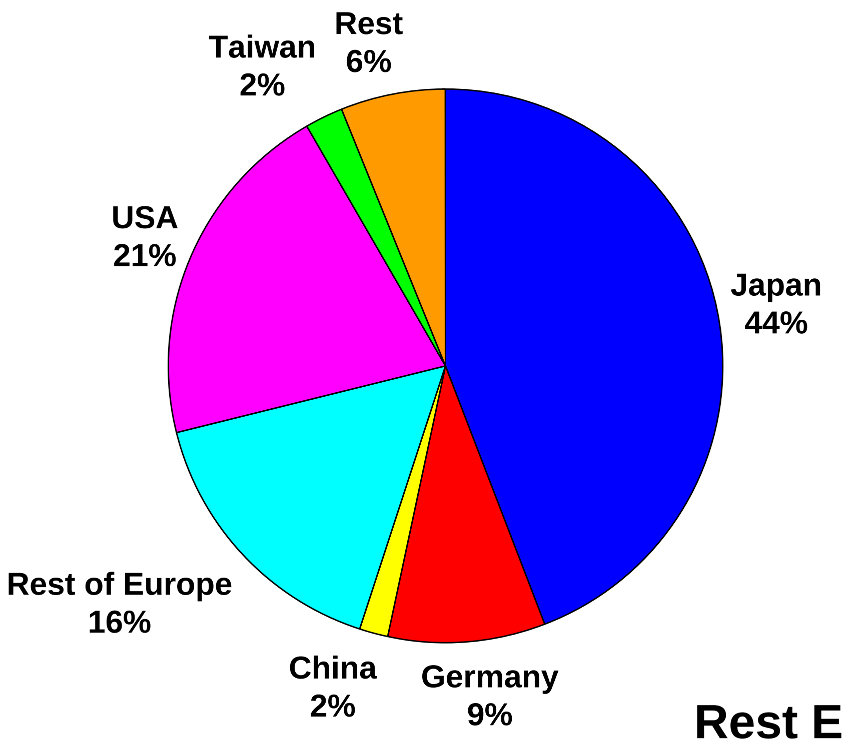
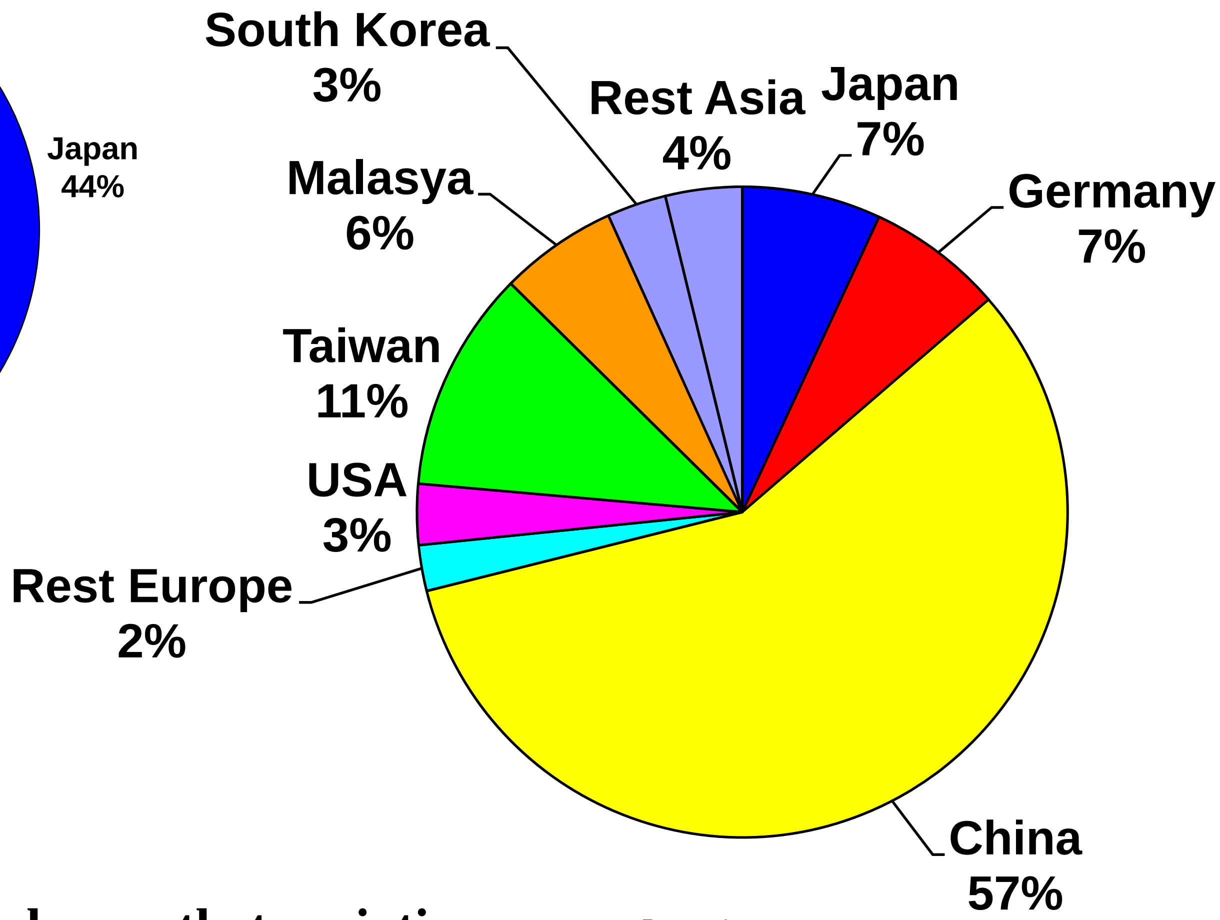
Solar cell production around the world

Photon International, 3/2003 & 3/2012



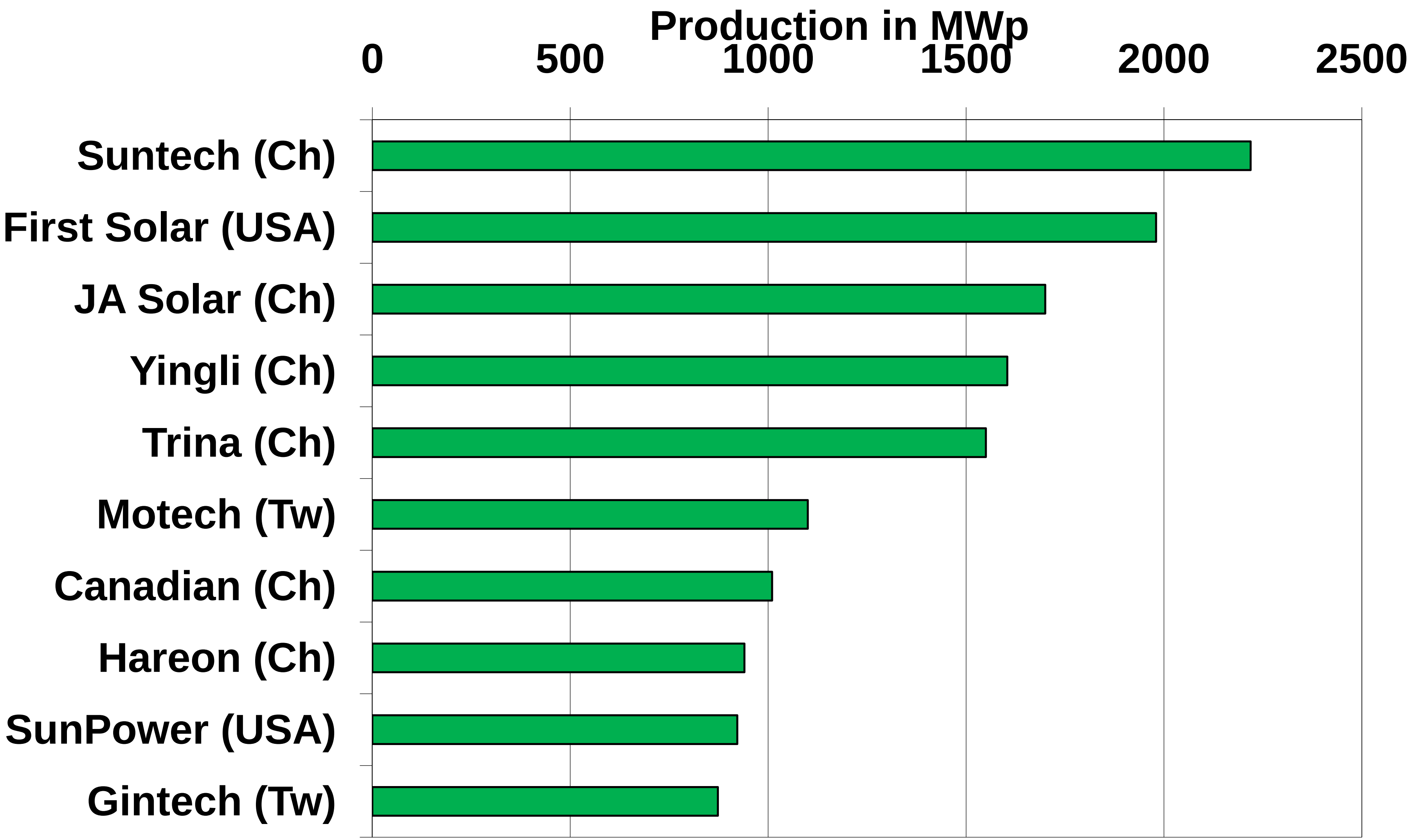
Production 2002



Production 2011

Production has moved recently to asiatic countries, specially China

Solar cell production: top ten



Photon International 3/2012

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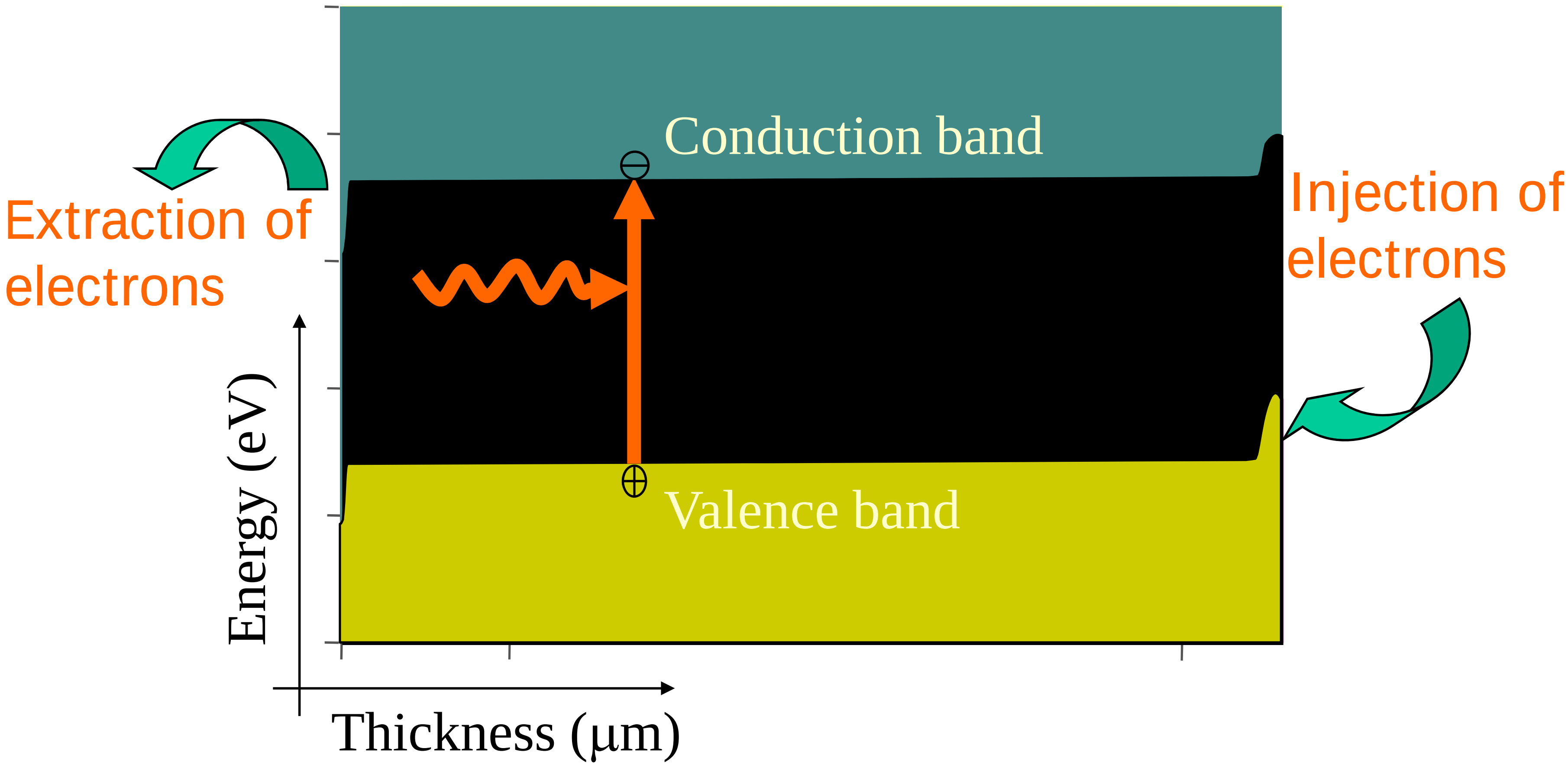
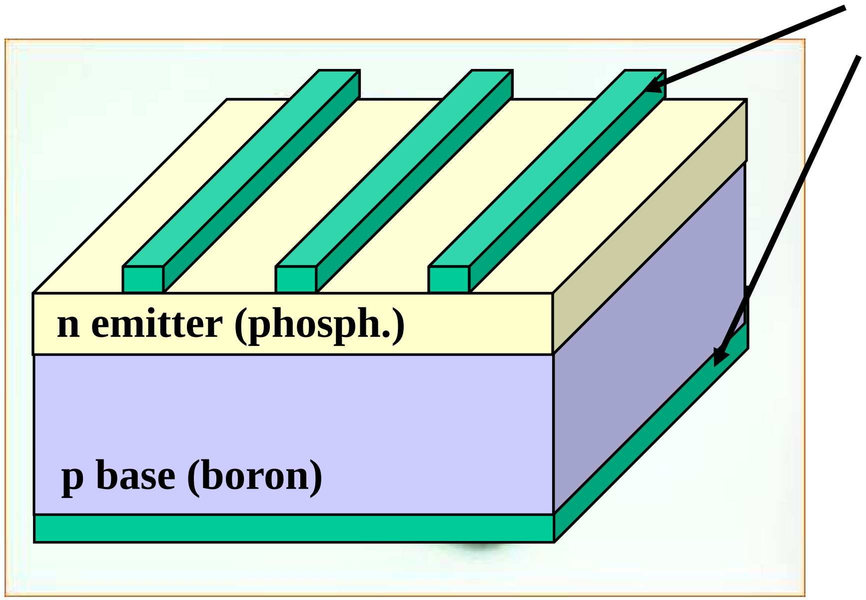
The grounds of the photovoltaic effect



- **Photons pump electrons from valence to conduction band**
- **Appropriate contacts insure conduction band electrons are delivered to load and recovered by the valence band**

Design of solar cells

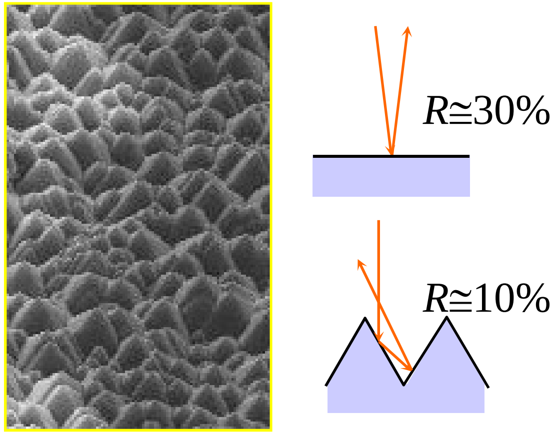


Cell is design to maximise the power delivered:

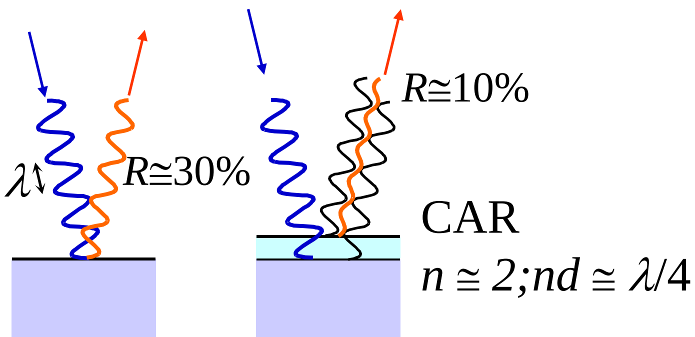
- **Increasing generation of e^{-} / h^{+} pairs (i.e, absorption of light)**
- **Reducing recombination (in bulk and surface)**
- **Minimising resistive effects**

Increasing light absorption

✓**Texturing**



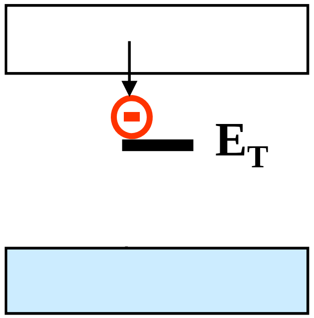
✓**Anti-reflection coatings**



✓**Texturing + anti-reflection coating ⇒ R≅1%**

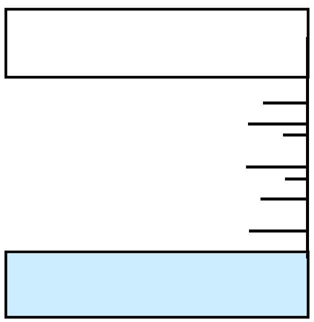
Recombination losses

Crystalline defects and metal impurities produce recombination through traps:



- ✓**Use of high quality materials**
- ✓**Fabrication in "clean rooms"**
- ✓**Techniques to *getter* contaminant impurities**
- ✓**Techniques to reduce recombination action of defects (*hydrogenation*)**

Surface, a radical discontinuity in the crystal:



- ✓**"Passivation" of dangling bonds by deposition of dielectrics**
- ✓**Diffusion of a dopant with the same type of the base (Back Surface Field)**

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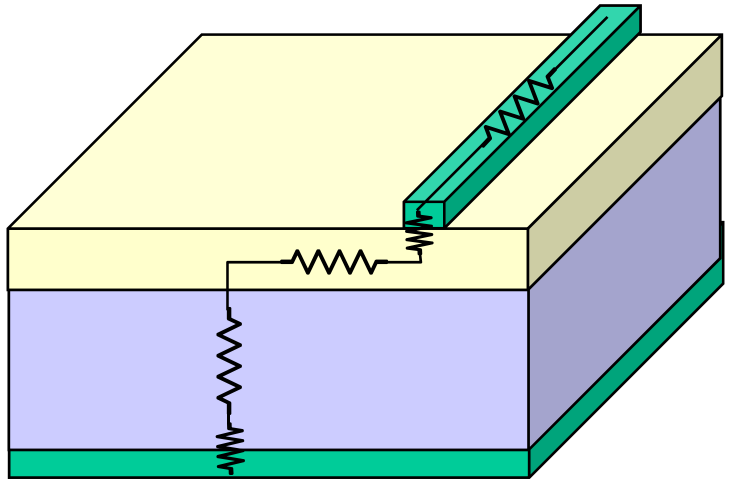
Resistive losses



✓**Bulk and emitter resistances, subject to compromises (recombination, voltage...)**

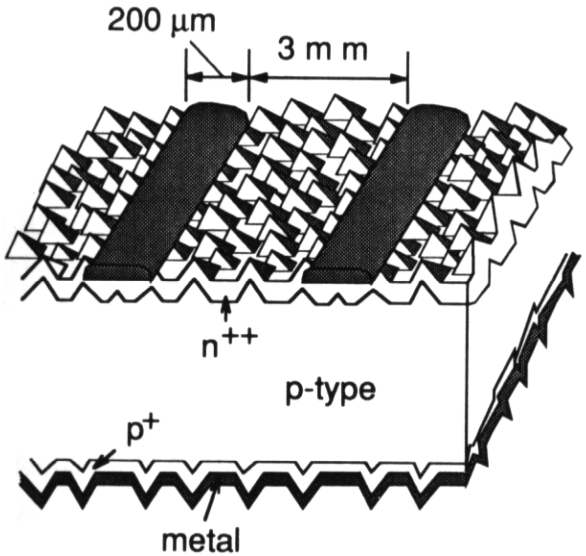
✓**Choice of appropriate metals (good contact, good conductivity)**

✓**Contact resistance is reduced for highly doped silicon**

✓**Design of metal grid subject to compromises (shadow, minimum finger width...)**

Solar cell structures

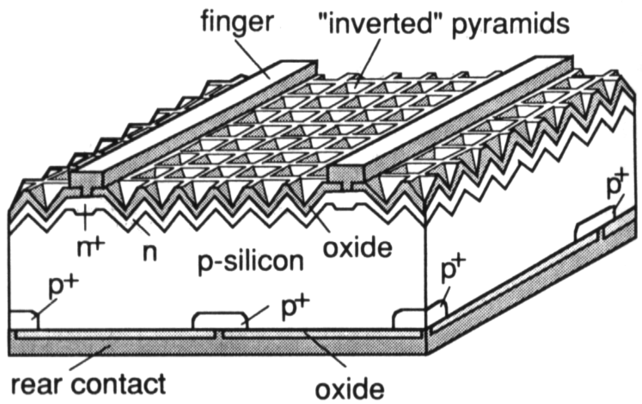
Industrial



•“Solar grade” substrates
•Reduced number of process steps
•Screenprinted metallisation

EFFICIENCY ≈ 16-18%

Laboratory



•High quality substrate (Float Zone)
•Processed at “cleanroom”
•Photolitography and metallisation by evaporation in vacuum

EFFICIENCY ≈ 25%

$$Efficiency = \frac{Electrical\ Power\ delivered}{Luminous\ Power\ received}$$

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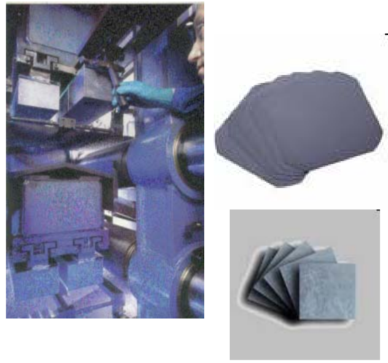
The Si value chain: from silica to systems

quartz →
carbon →

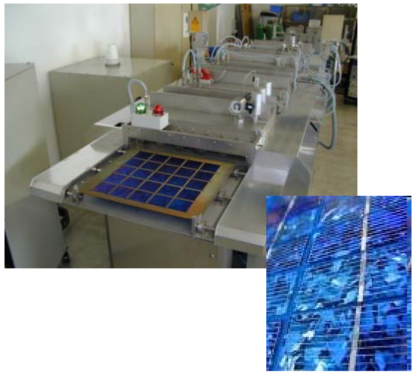
Reduction to metallurgical Si

Ultrapurification to polysilicon

Crystallisation



Wafering

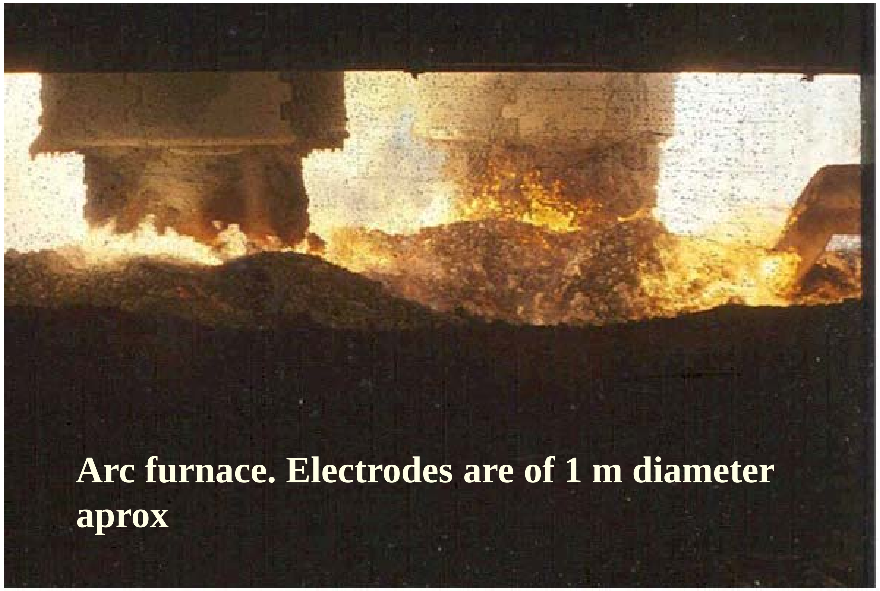


Solar cell processing

Module assembly

System implementation

Metallurgical silicon production



Arc furnace. Electrodes are of 1 m diameter aprox

- **Reduction of quartz with carbon in an arc furnace** $SiO_2+2C \rightarrow Si+2CO$
- **Product: metallurgica silicon, 99% pure**
- **Electronics and Photovoltaics only use a small fraction (~10-15%) of the total production, which is devoted mainly to metallurgical industry**

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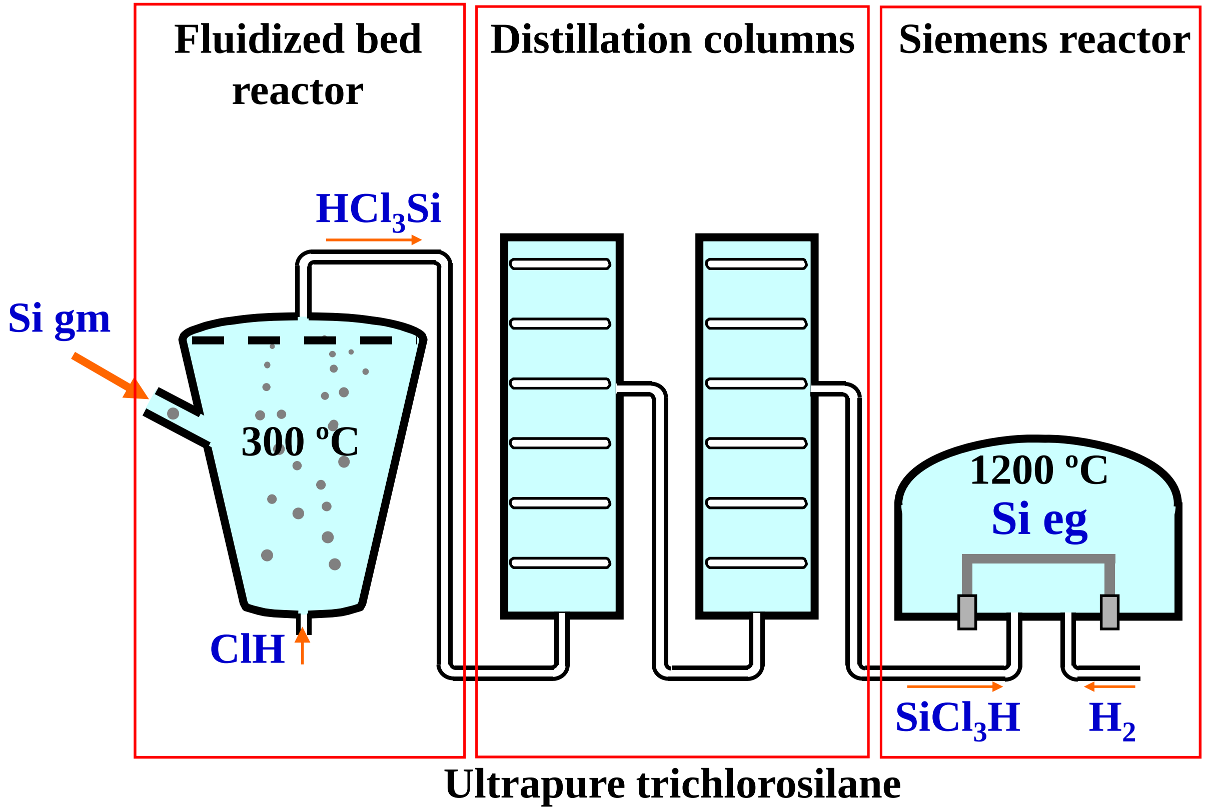
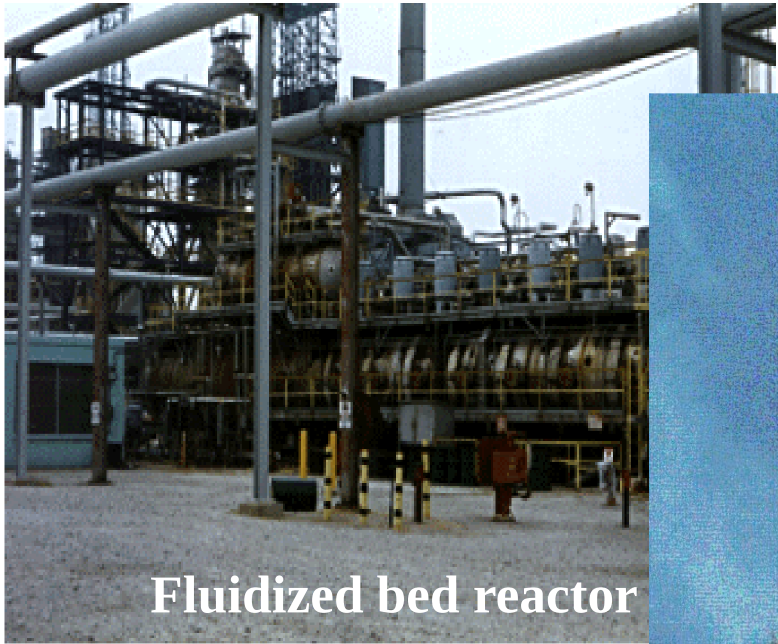
Electronic grade silicon production (polisilicon)



$3HCl + Si\ (gm) \rightarrow HCl_3Si + H_2$ $\qquad$ $4HCl_3Si + H_2 \rightarrow Si\ (ge) + 3SiCl_4 + 3H_2$

- **Raw materials: metallurgical silicon and HCl**
- **Product: Electronic grade silicon (99.9999999% pure)**
- **High energy consumption (100 kWh/kg)**



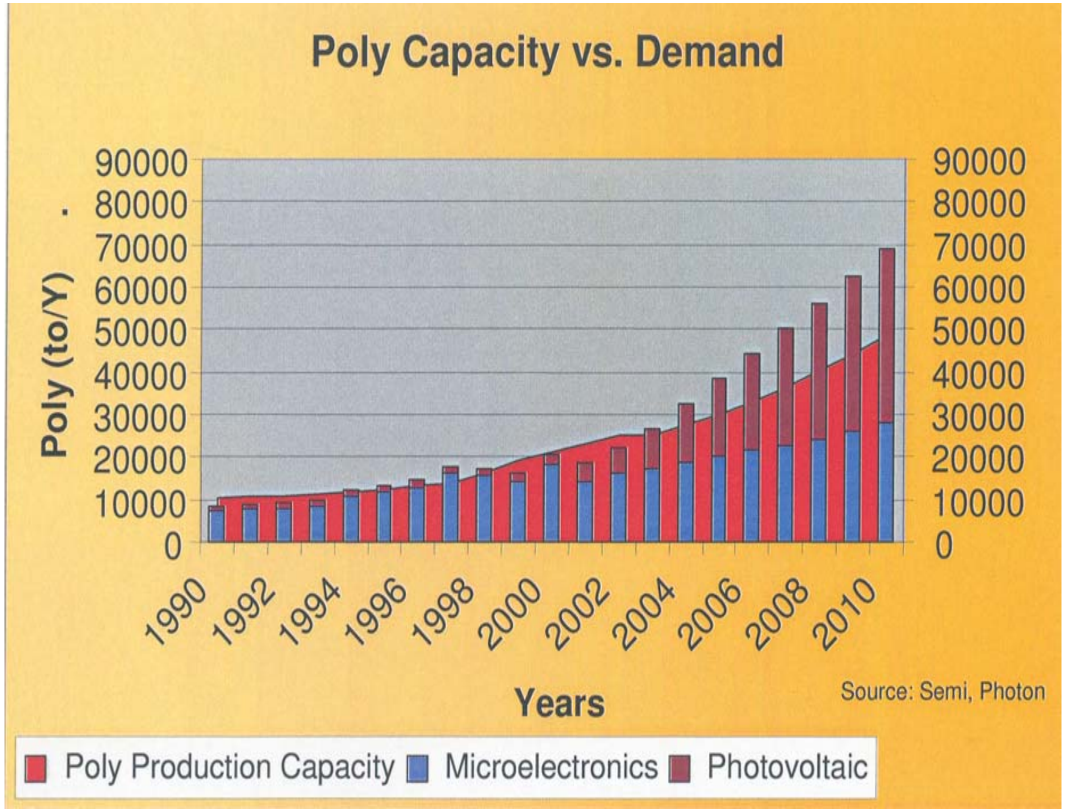
Fluidized bed reactor

Distillation column

Polisilicon

The revolution in the Si feedstock market

P. Fath, A. Mozer, 3rd Solar Si Conf, 2006



- **2006-2007: Silicon shortage**
  - **- Slow reaction of polysilicon producers to expand capacity**
  - **- New entrants trying to acquire the technology**
  - **- Intensive R&D on polysilicon purification for solar**

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The revolution in the Si feedstock market (2)

- **2009: Quick change of scenario towards oversupply**
  - **New capacity installed in a context of market slow-down**
  - **Pressure on new entrants, that need to demonstrate good material quality and low costs**

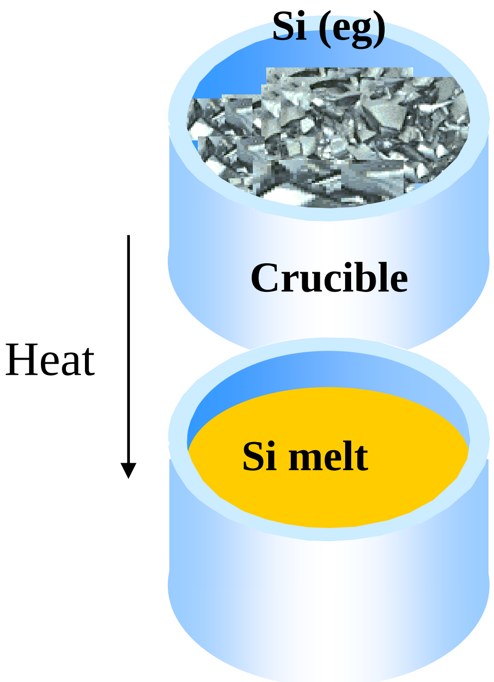
- **In the medium and long run:**
  - **PolySi production structure changing to a "distributed" one: ~5000 t of Si for a 1000 MWp PV plant**
  - **Technology changes when targeting "Solar Silicon"**

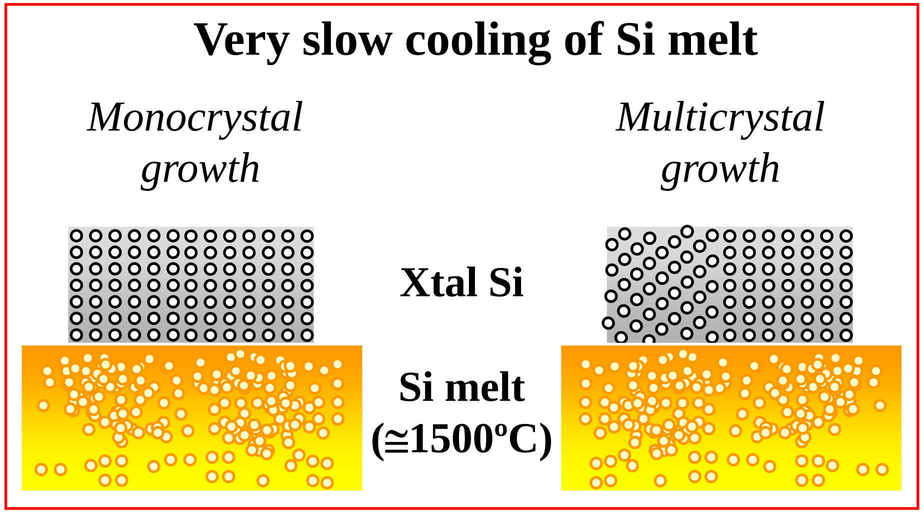
Solar Silicon

→ Simplifying chlorosilane process
-Silane as volatile compound
-Alternatives to Siemens deposition system

→ Applying metallurgical steps
-Directional solidification
-Slagging
-Evaporation in vacuum
-…

Crystallisation

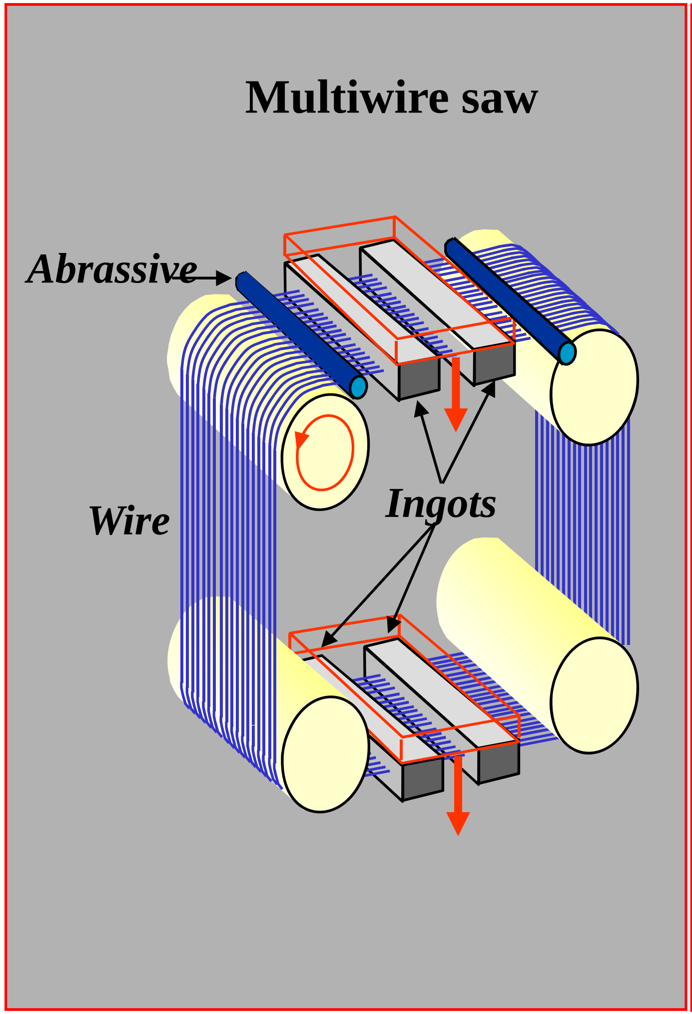


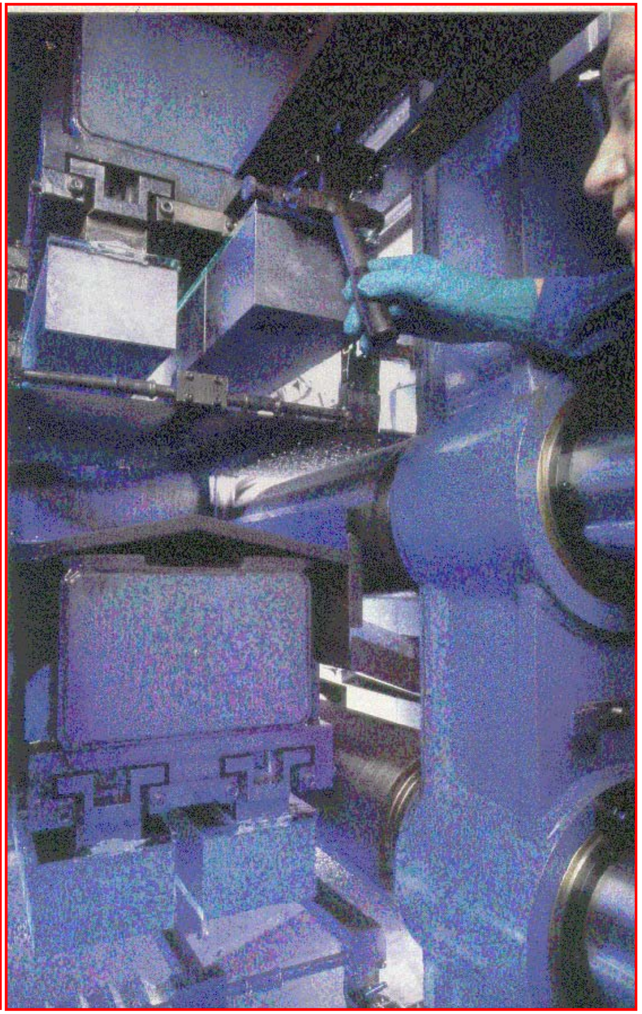



Monocrystalline ingot

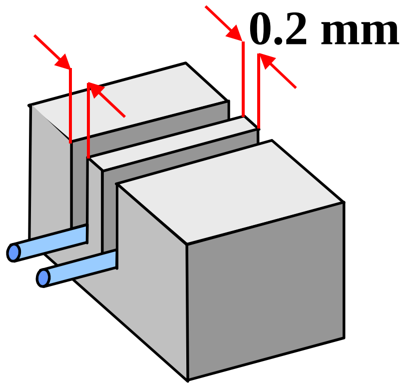

Multicrystalline ingot in blocks

Wafering



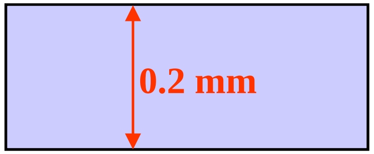


Kerf losses of around 50%

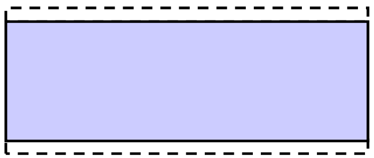


Solar cell processing (I)

Wafers 156 cm^2 p-type (B 10^{16} cm^{-3})

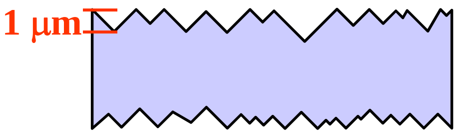


Cleaning and etching



KOH

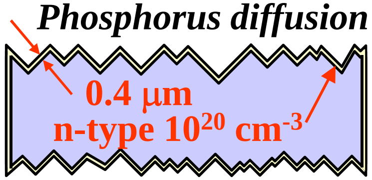
Texturing



KOH bath
85 ºC

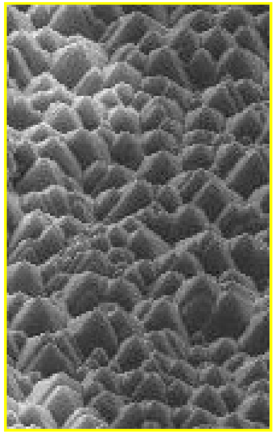
Cleaning

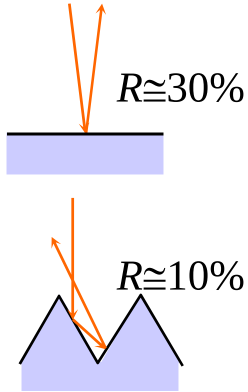
Phosphorus diffusion

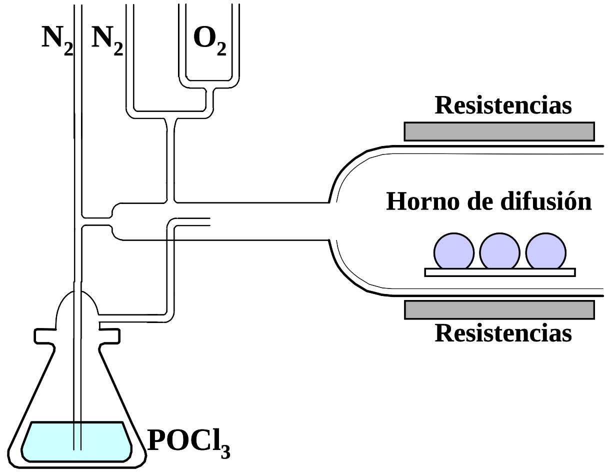


900 ºC, 1/2 h

Cleaning

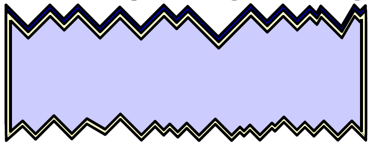




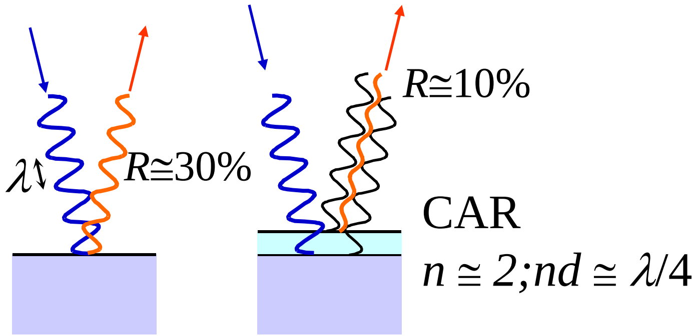


Solar cell processing (II)

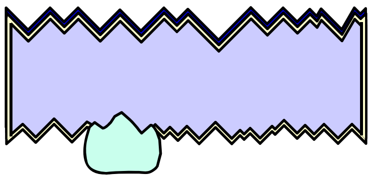
Anti-reflecting coating



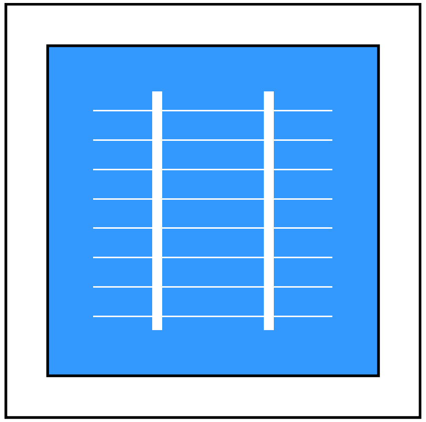
CVD
SiN_x:H



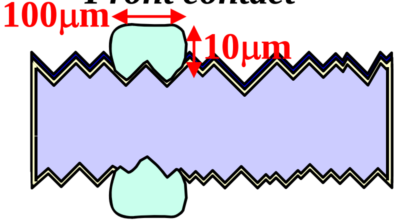
Rear contact

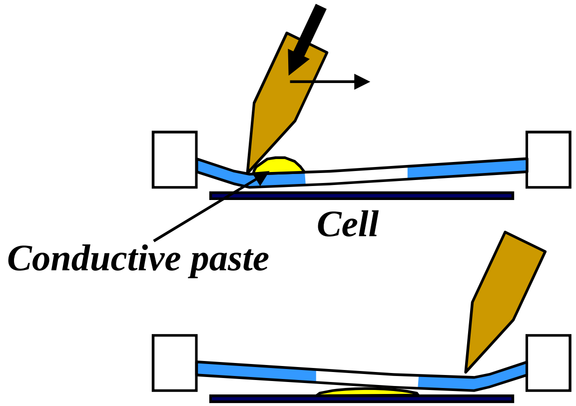


Screenprinting of
a conductive paste
Fired in a IR furnace
(800°C,10 min)

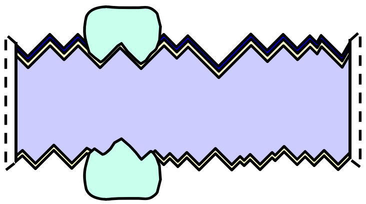


Front contact





Junction isolation

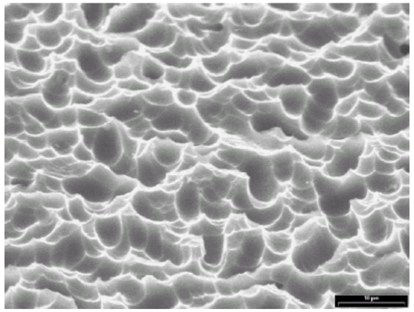


Plasma
etch

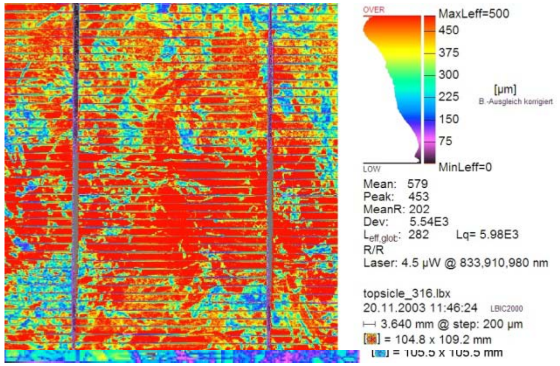
Measure and classify

Solar cell processing for multicrystalline Si

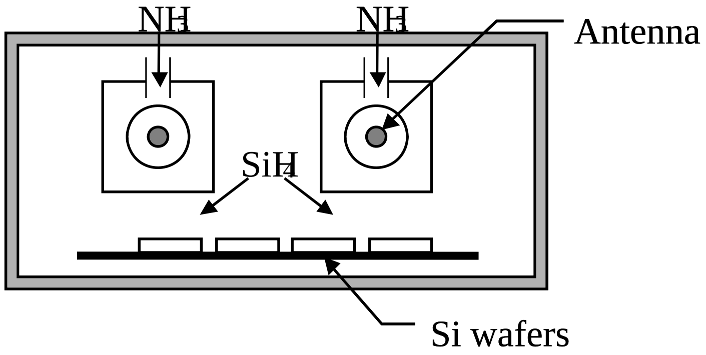
Alternatives to alkaline texturing: acidic texturing, RIE,...

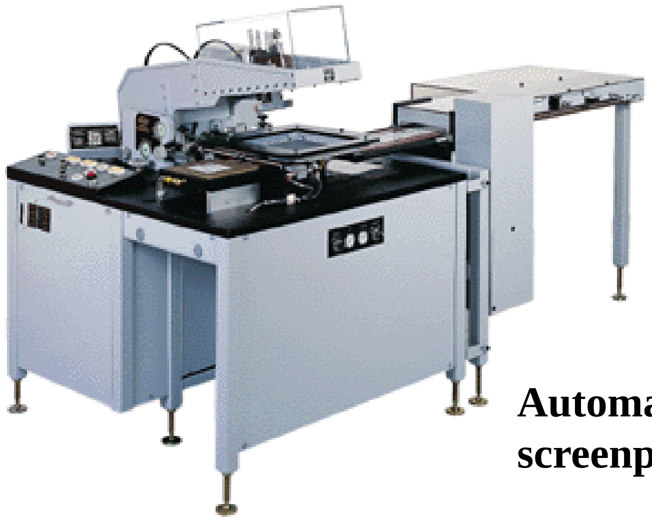


Integration of taylored *gettering* processes

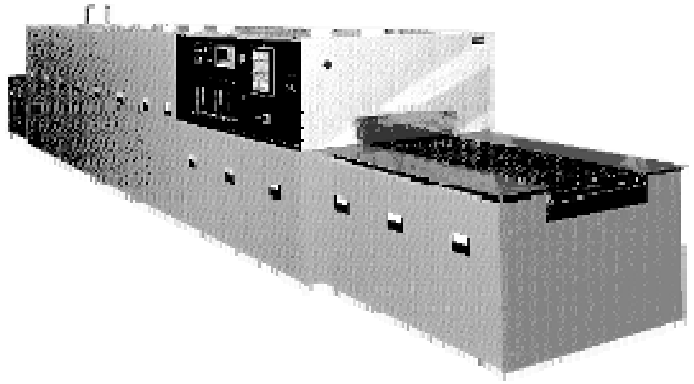


Hydrogenation by Plasma-Enhanced Chemical Vapor Deposition during the SiNx AR coating

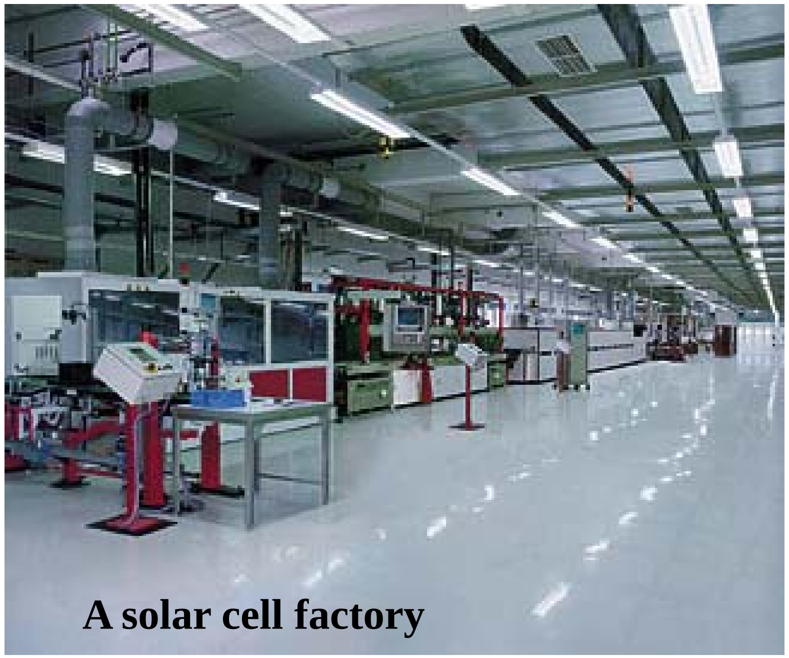




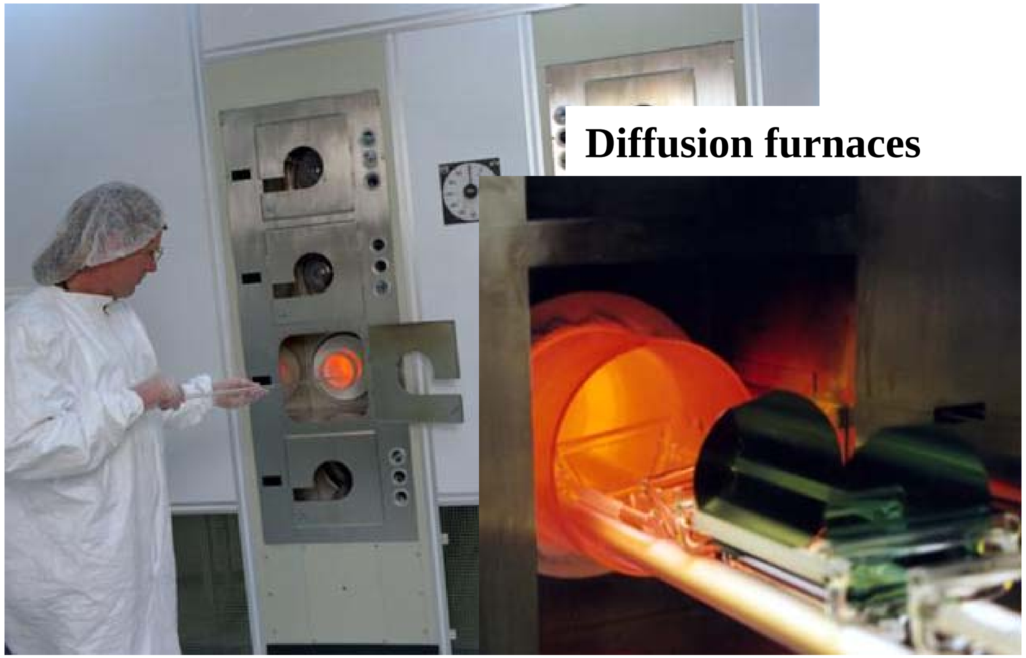
Automatic screenprinter



In-line furnace for firing

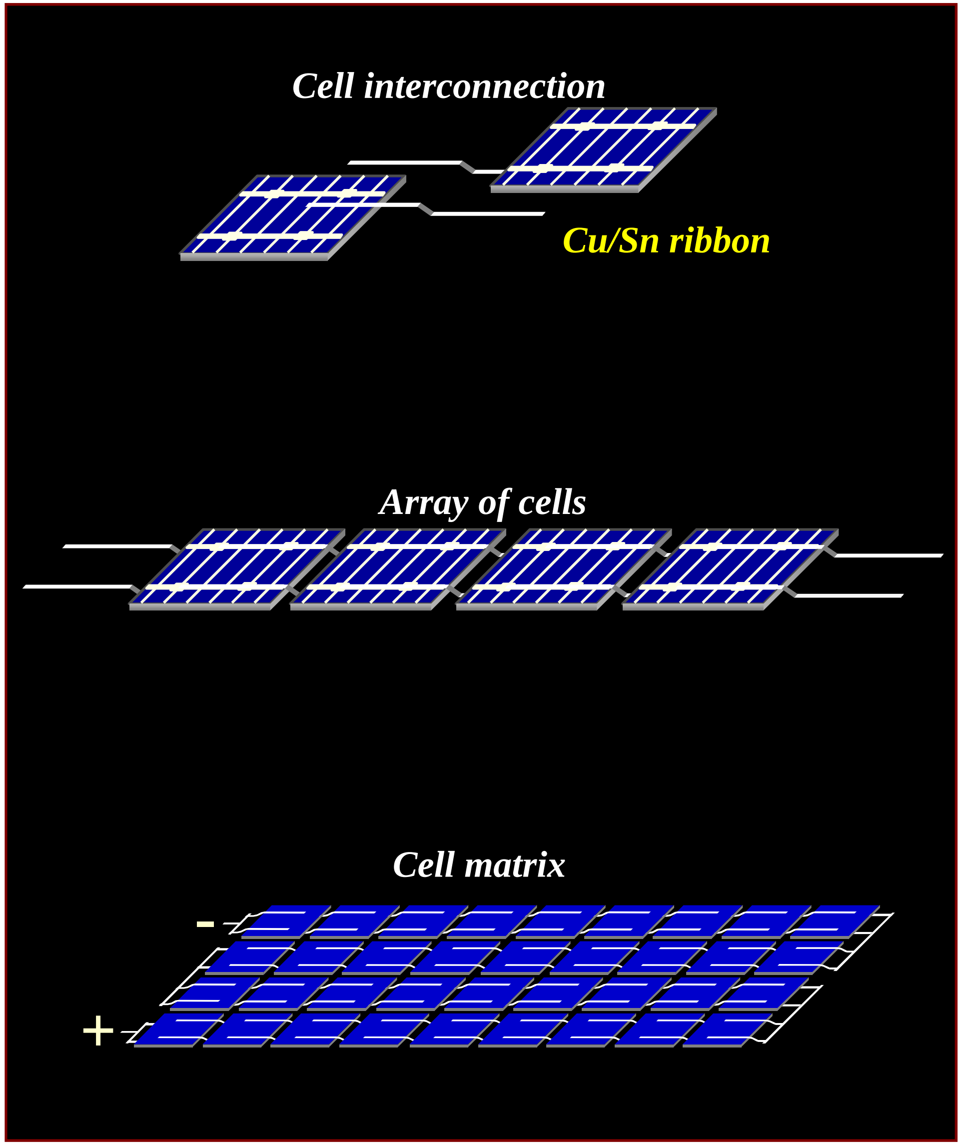


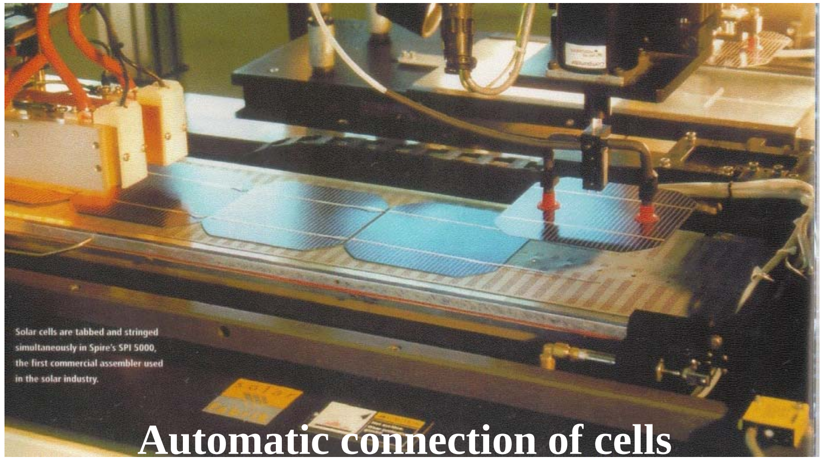
A solar cell factory



Diffusion furnaces

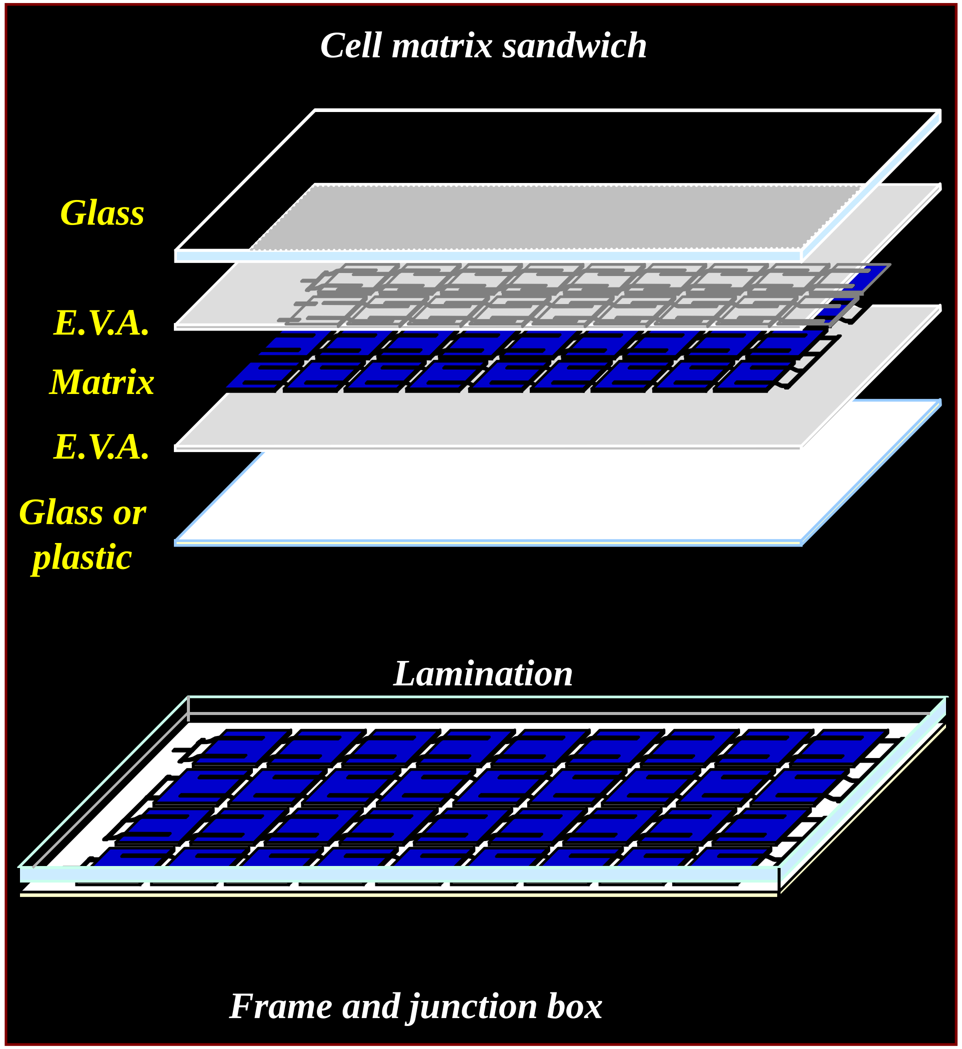
Module assembly (I)





Automatic connection of cells

Module assembly (II)



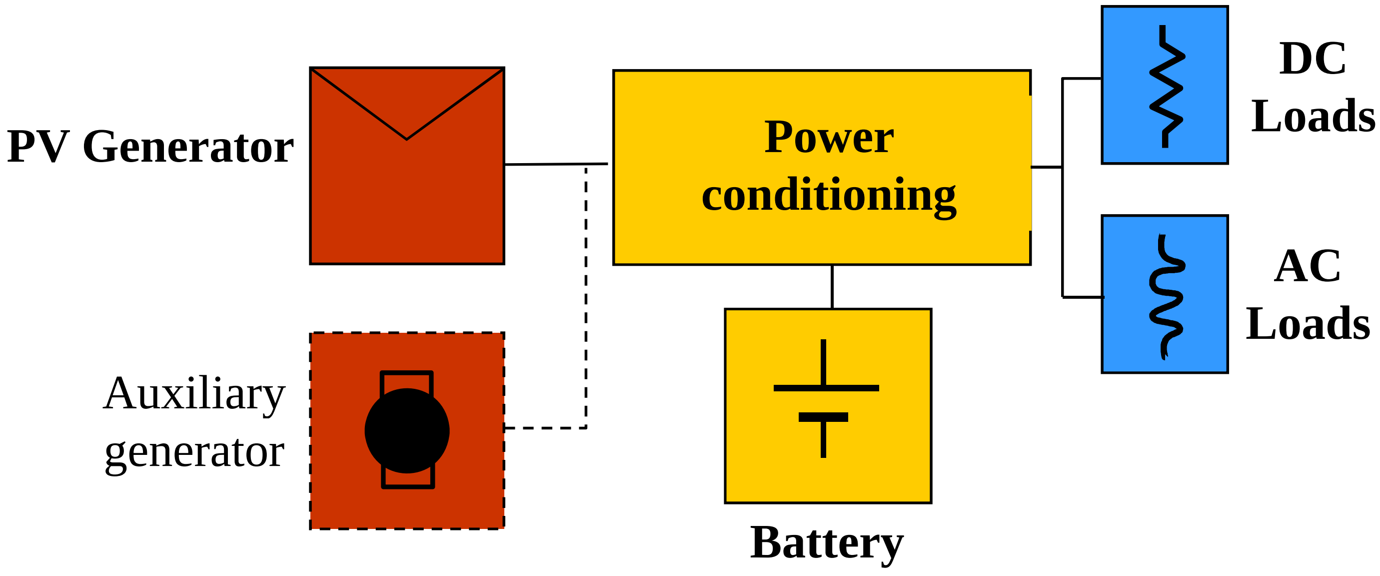
Lamination:

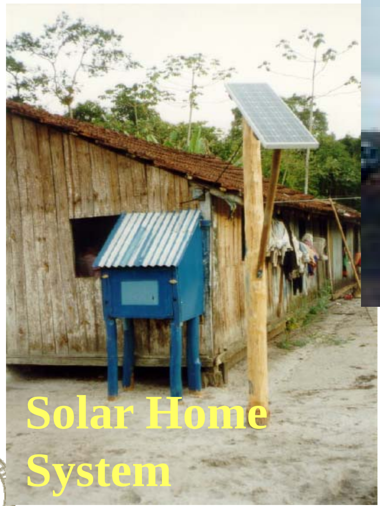
Pressure at 100ºC + Curing at 150ºC:

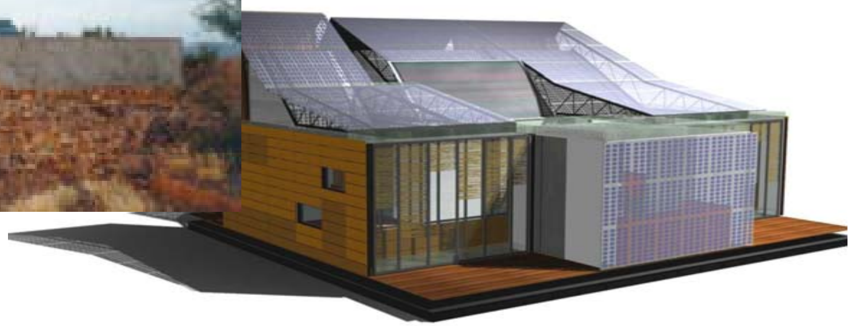
Cells are soaked in the flowing EVA, which becomes transparent and solidifies

Laminator

Off-grid instalations

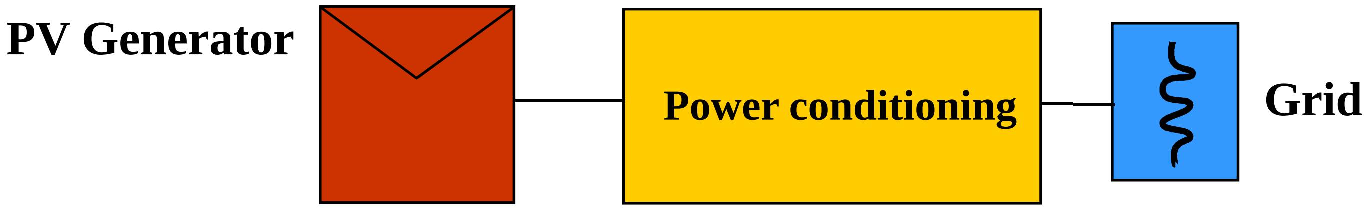






Isolated residential

Grid connected instalations



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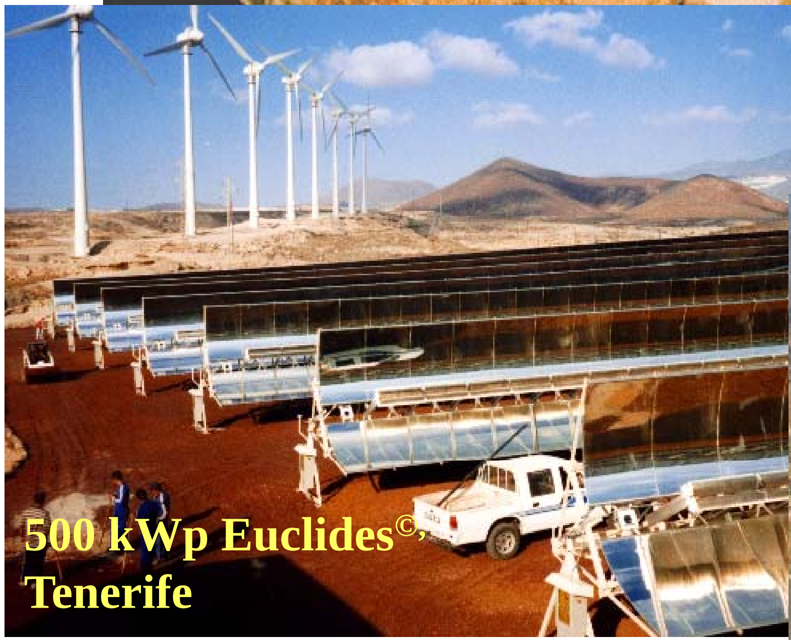
Solar farms


PV Toledo, 1 MWp


Navarra, 9 MWp


500 kWp Euclides©,
Tenerife


Cuenca, 60 MWp

BoS equipments

Batteries

Regulator

DC/AC
converters

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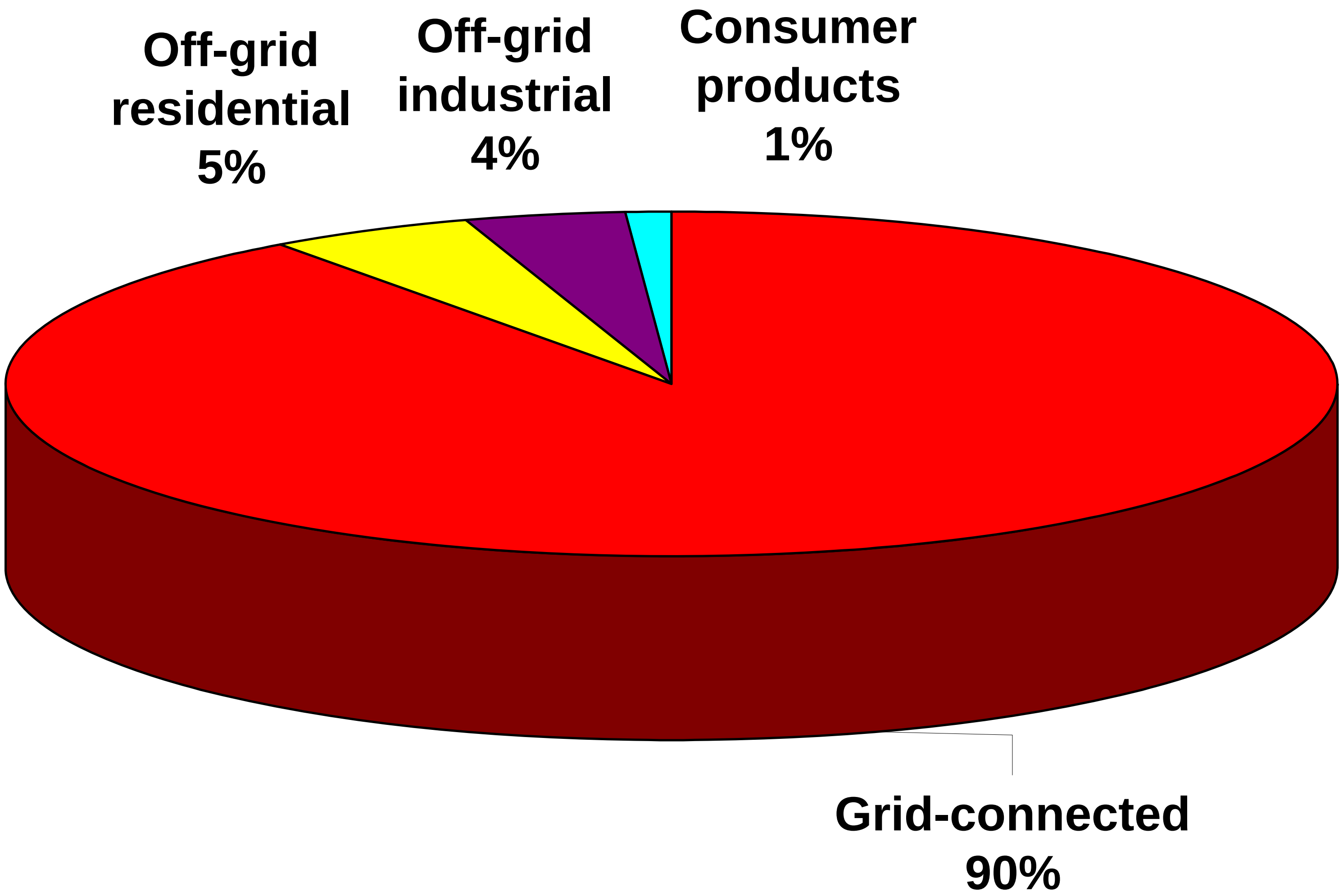
PV market breakdown (2007)

EPIA/Greenpeace, 2008



Introduction

Crystalline silicon technology, from quartz to system

Economical and environmental issues

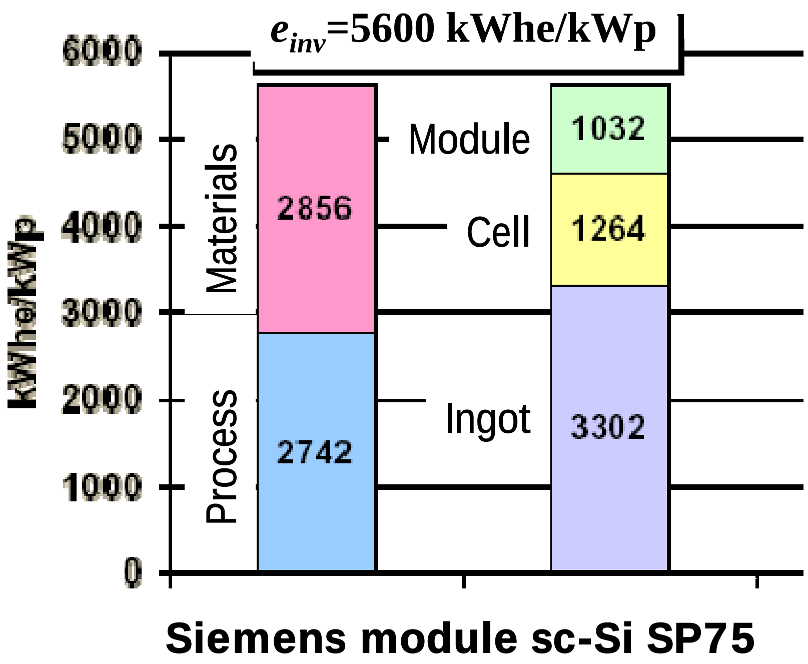
Alternatives to cristalline silicon technology

Conclusions

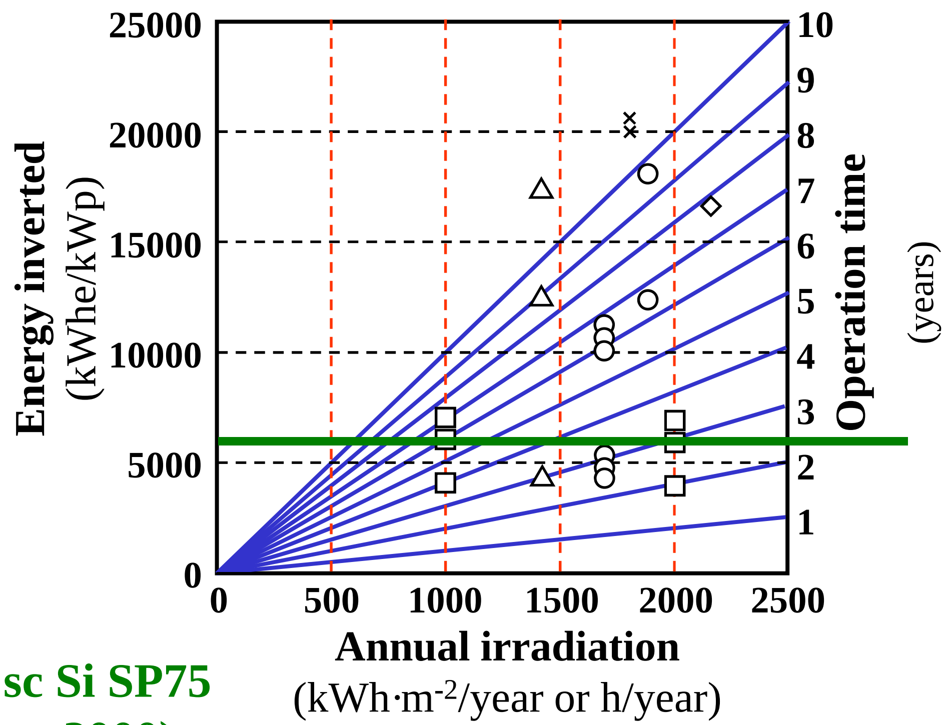
Energy Pay Back Time (EPBT)

Time needed by the PV system to give back the energy invested in its fabrication

$$EPBT = \frac{Invested\ energy}{Energy\ \ produced\ in\ a\ year}$$



K. Knapp y T. Jesters, "PV payback". *Home Power*, **80** (2001)



Siemens module sc Si SP75 (Knapp & Jester 2000)

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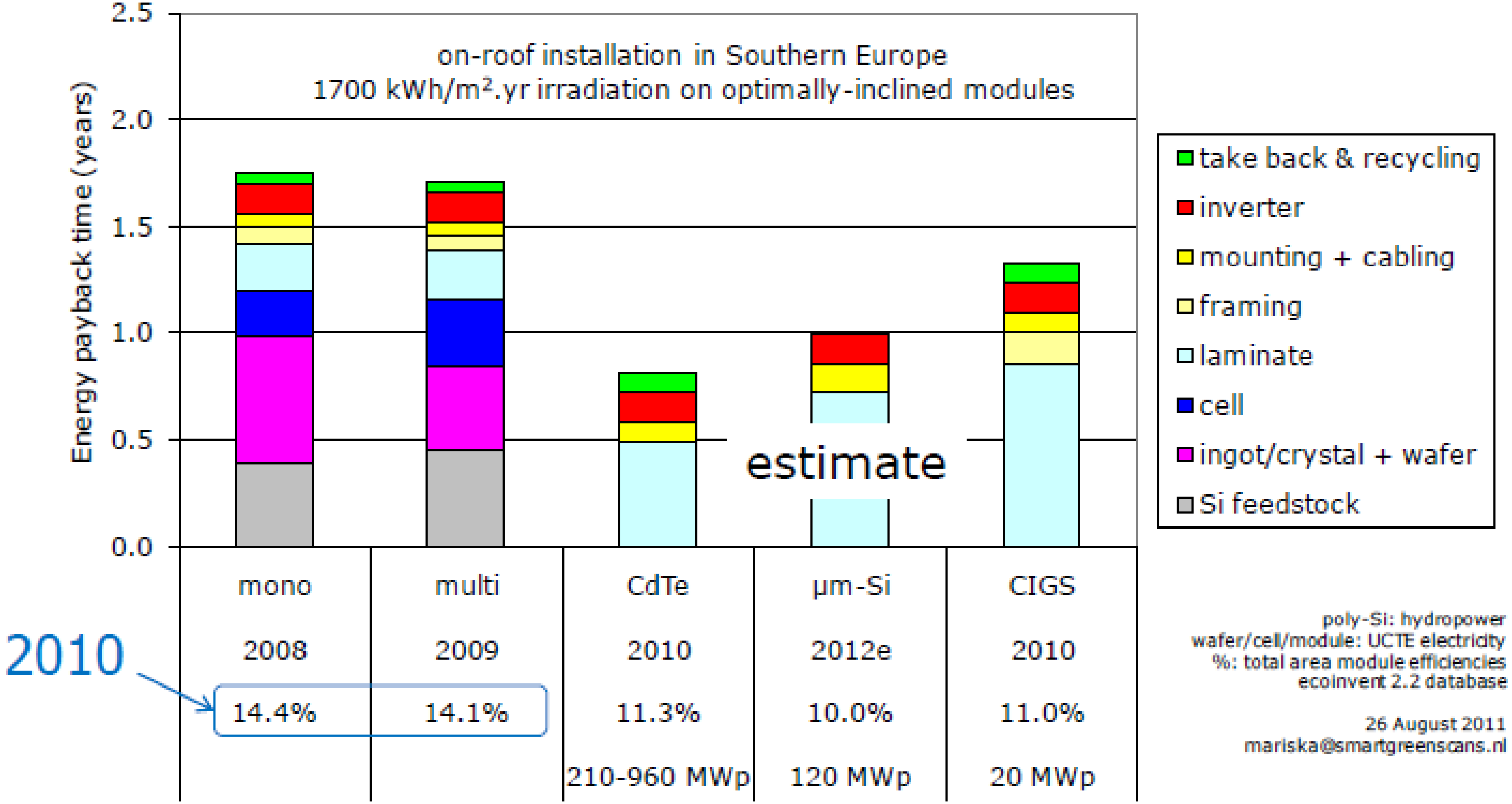
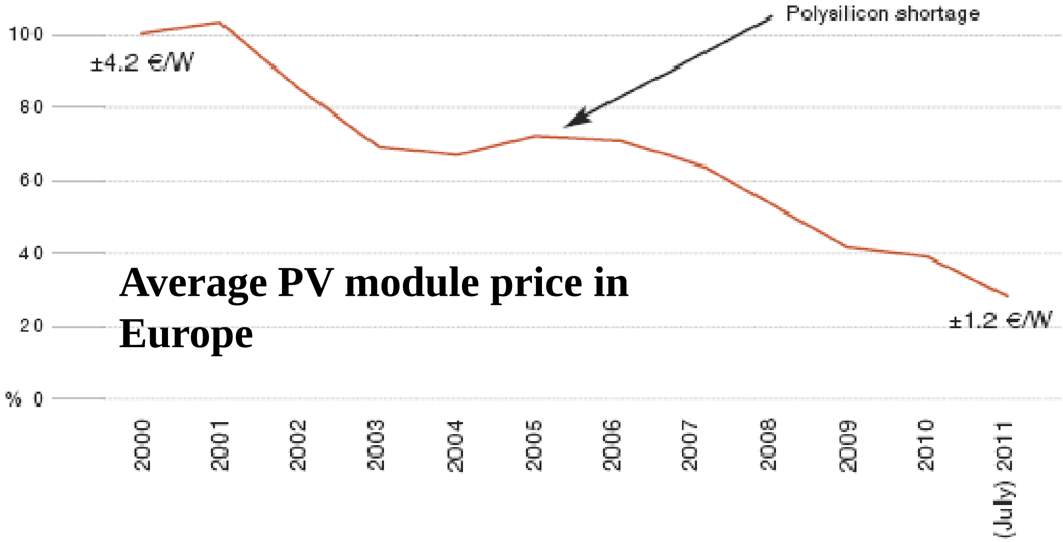
Energy Pay Back Time (II)



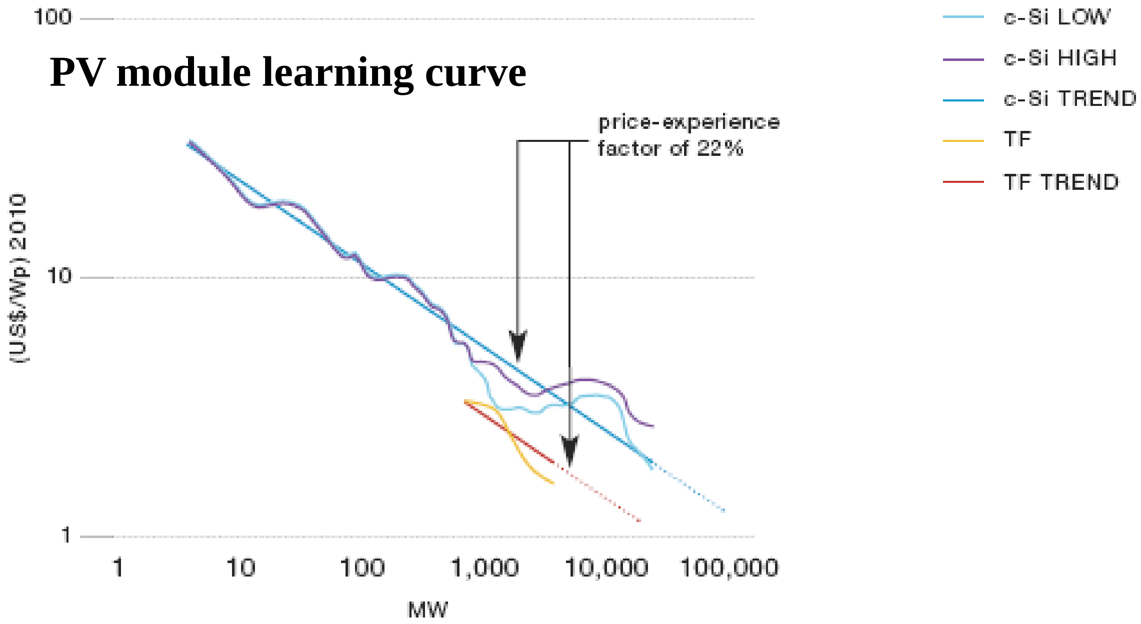
Source: **de Wild-Scholten, 26th European PVSEC, 2011**

Evolution of technology price

EPIA 2011



Average PV module price in Europe



PV module learning curve

Steady reduction of PV price, closing the gap to competitiveness

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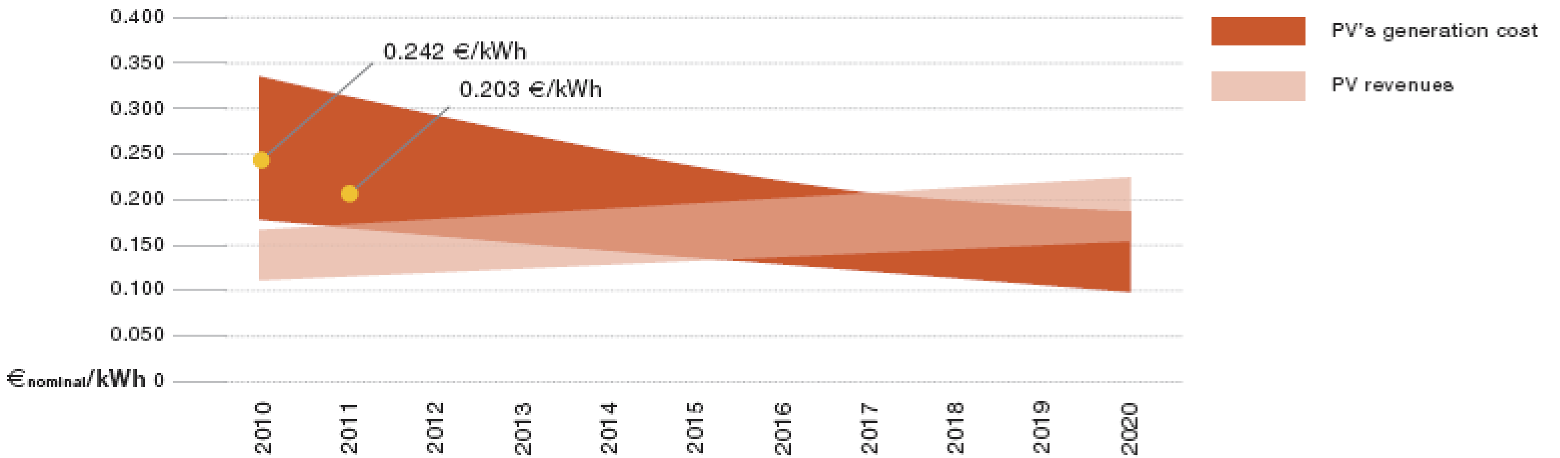
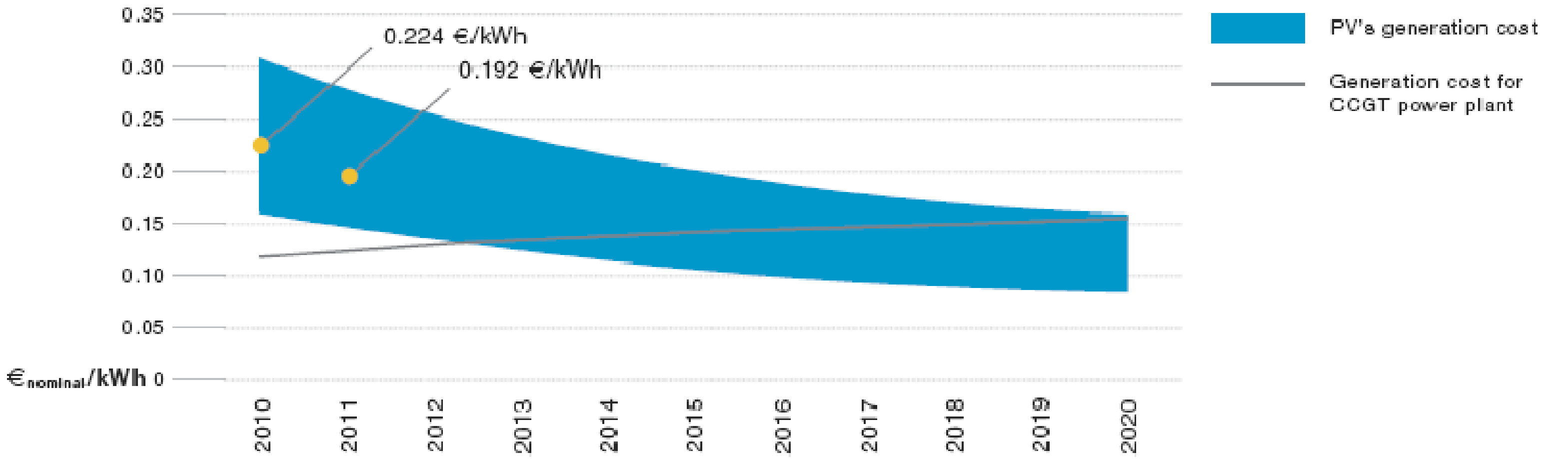
Evolution of technology price (2)

EPIA 2011

PV commercial system (100 kW)



Large ground-mounted PV system (range of MW)



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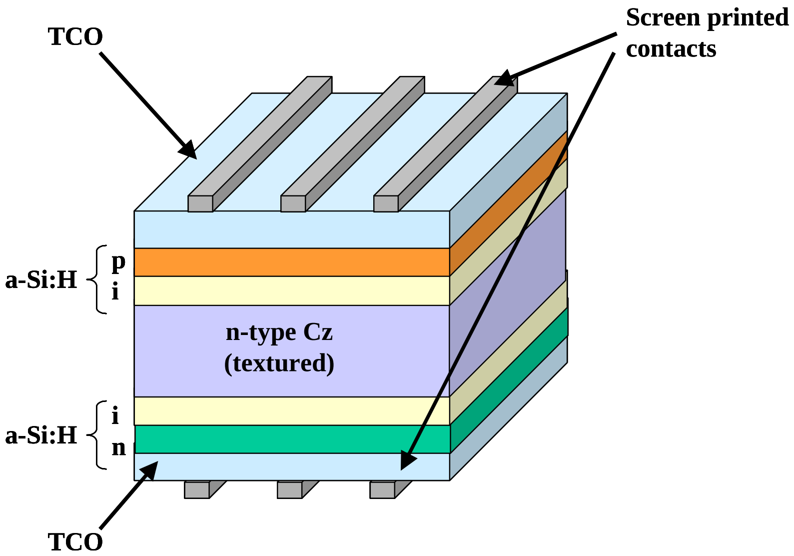
Most major EU markets can reach competitiveness before 2020 under a mature market assumption

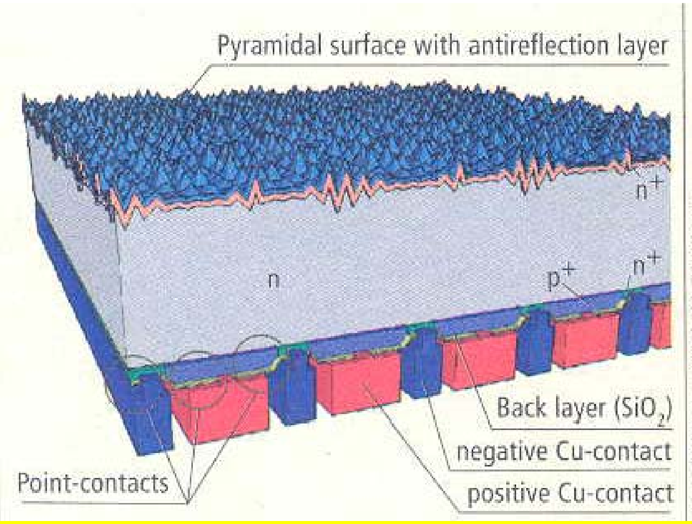
Advanced crystalline silicon technologies

HIT:Heterojunction with Intrinsic Thin layer (Sanyo)



- n-type wafers
- a-Si layers deposited at 200ºC.
- Efficiencies at industrial level > 20%
- Bifacial structure

Point-Contact Cell (SunPower)



- Both p+ and n+ contacts at the rear, with two alternated "comb-like" structures
- Use of highest quality wafers
- Efficiencies at industrial level > 22%

Introduction

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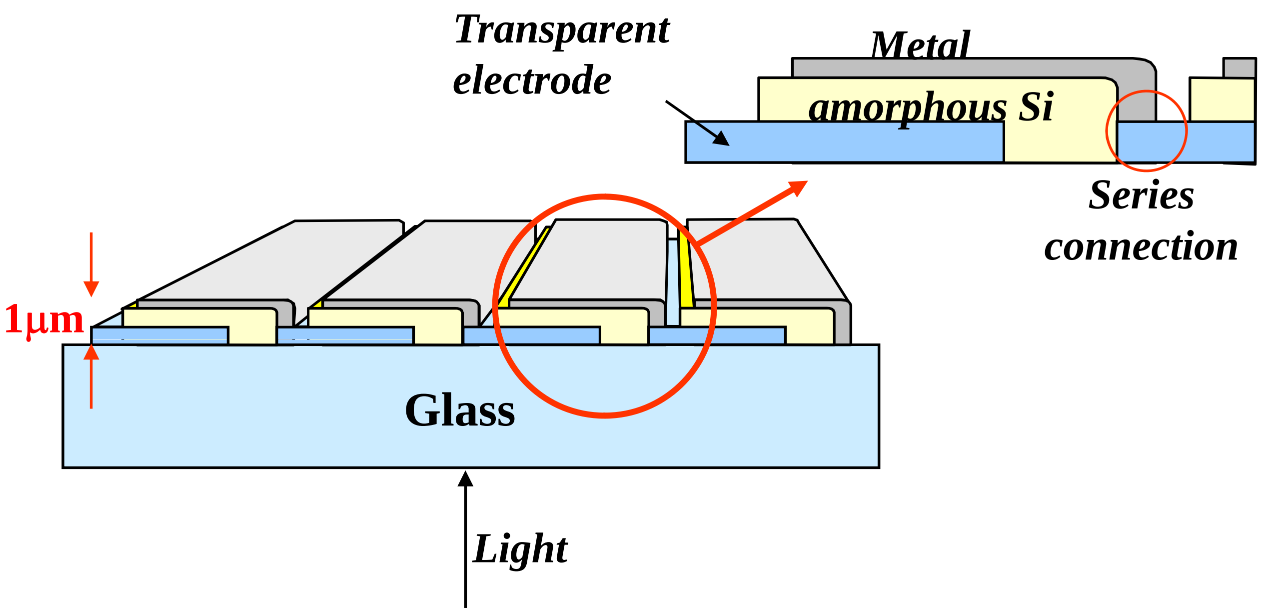
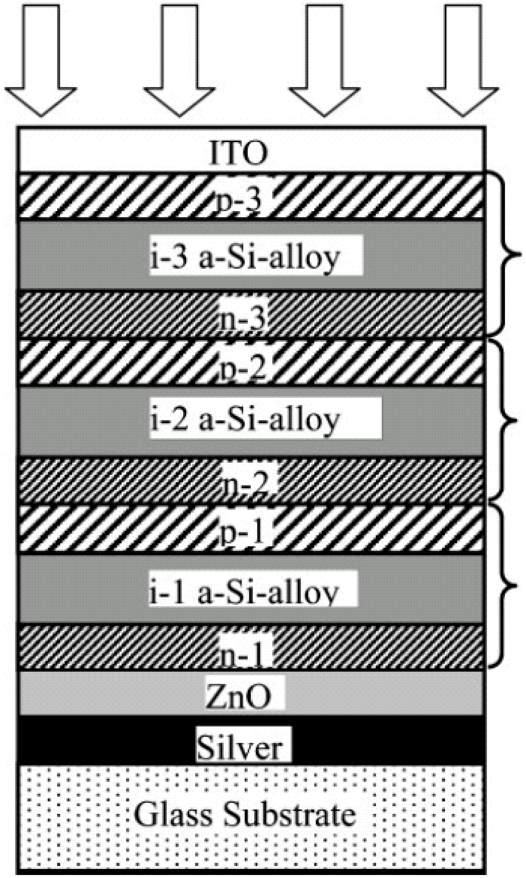
Low cost approaches: Thin films

A big portion of light is absorbed in the first few microns (depending on the material): posibility to SAVE material

Direct fabrication of the module: layers are deposited and interconnected on the substrate (the glass, for instance)

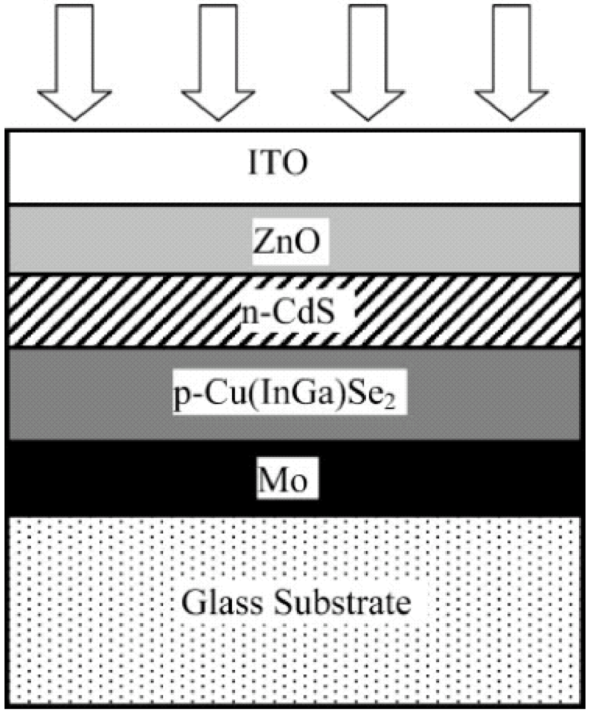


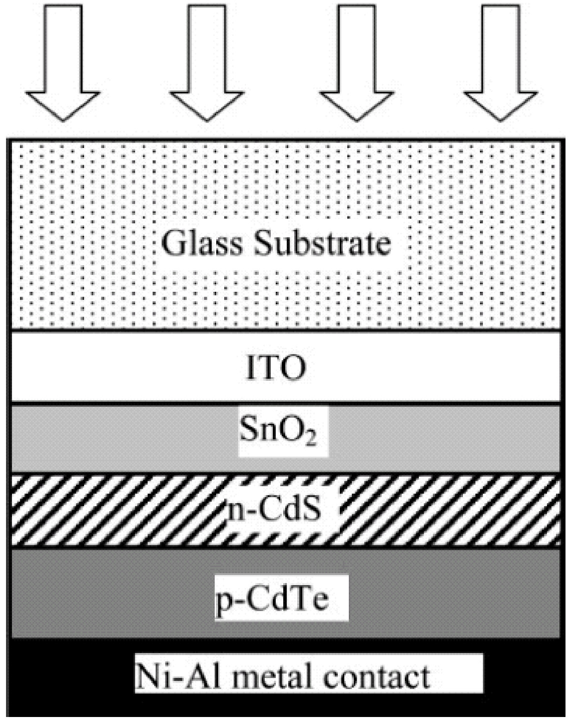
Thin films: a-Si:H



	a-Si:H
	$E_G \cong$ **1.3-1.8 eV**
Commercial module	$\eta \cong$ **7 %**
Laboratory cell	$\eta \cong$ **12.1 %**
Advantage	Cost, maturity
Disadvantage	Low estabilised efficiency

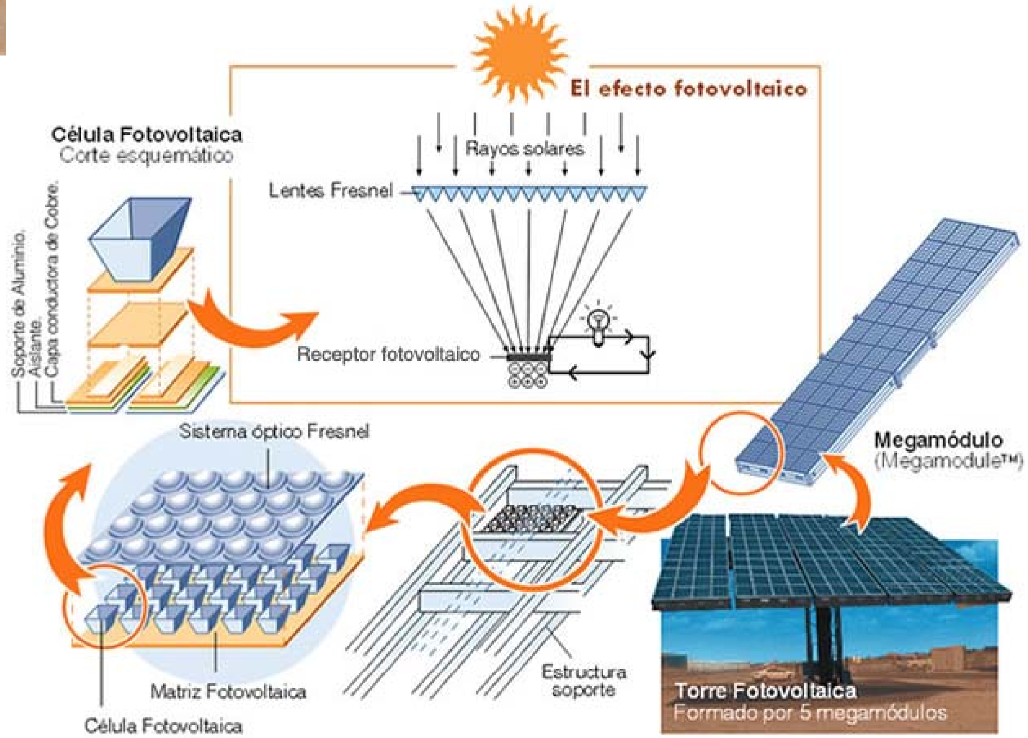
Thin films: CIS y CdTe



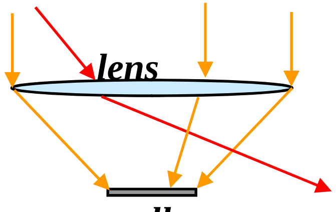


	CIS	CdTe
	$E_G \cong 1.1\text{eV}$	$E_G \cong 1.5\text{eV}$
Commercial module	$\eta \cong 12\ \%$	$\eta \cong 10\ \%$
Laboratory cell	$\eta \cong 20\ \%$	$\eta \cong 17\ \%$
Advantage	Higher efficiency	Lower cost
Disadvantage	Complex, scarcity of In	Scarcity and toxicity of Cd

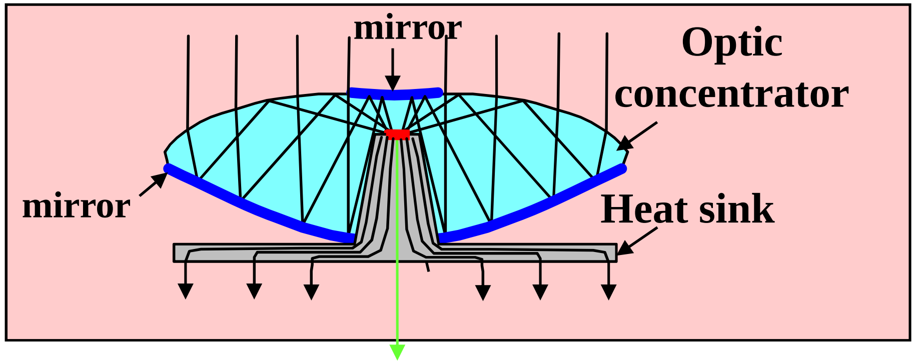
High efficiency approach: PV concentration



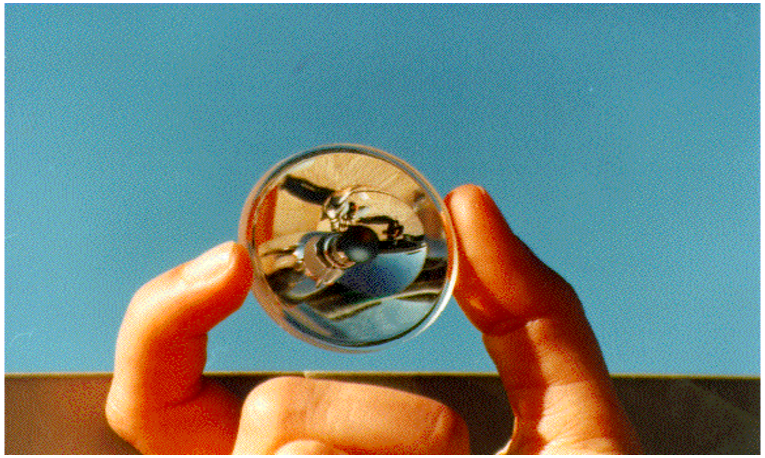
High eff. approach: high concentration with GaAs cells

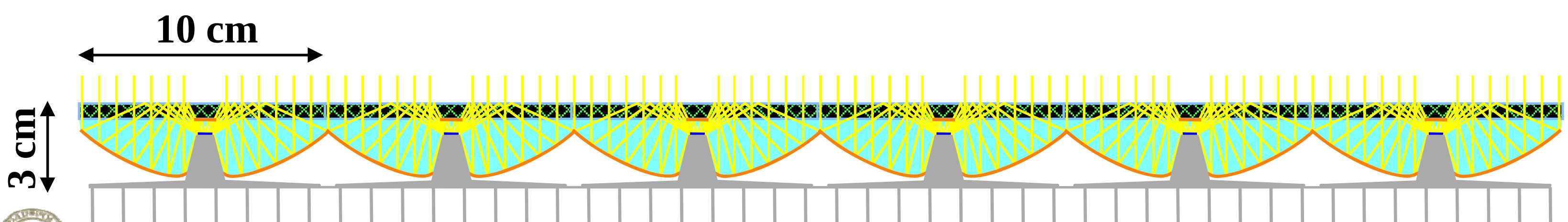


1.000 suns = 1 MW/m^2



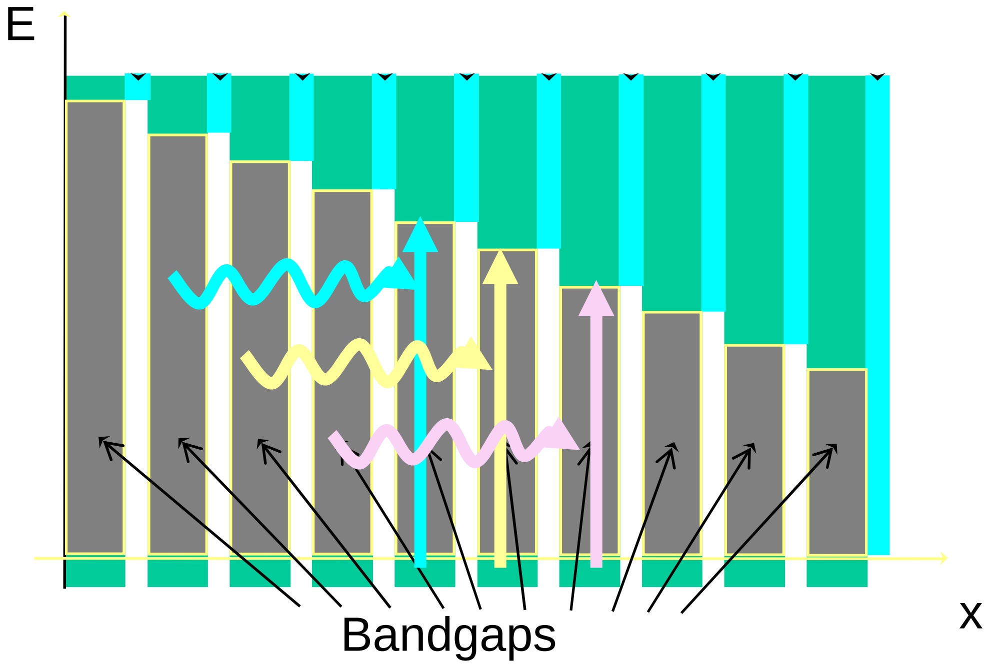
AsGa cell
~30-40% at high irradiation levels



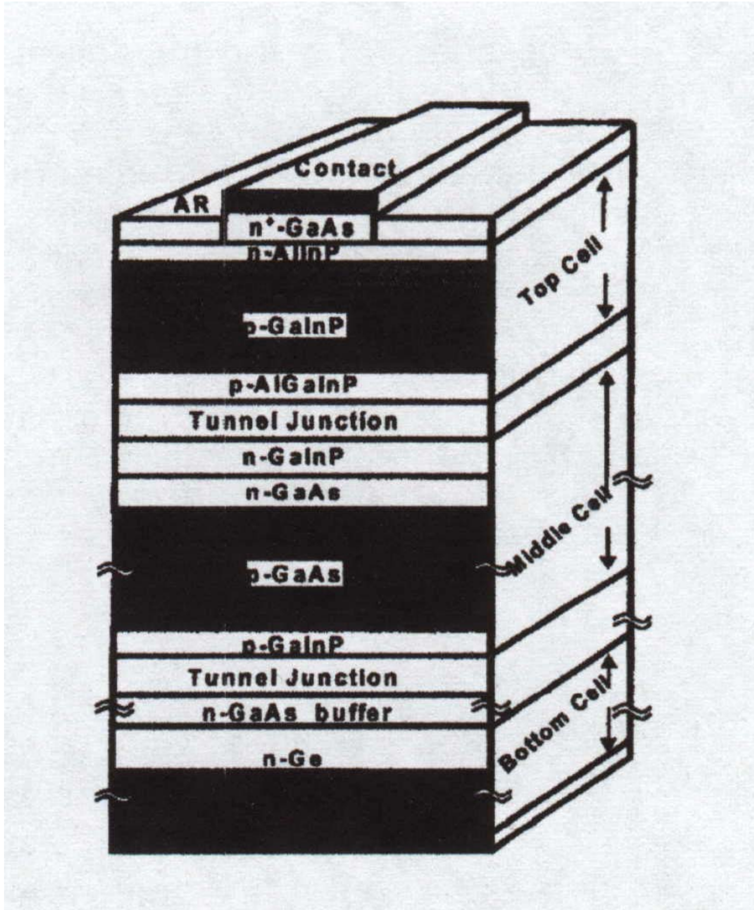


High efficiency approach: Third generation solar cells

- **Tandem cell**



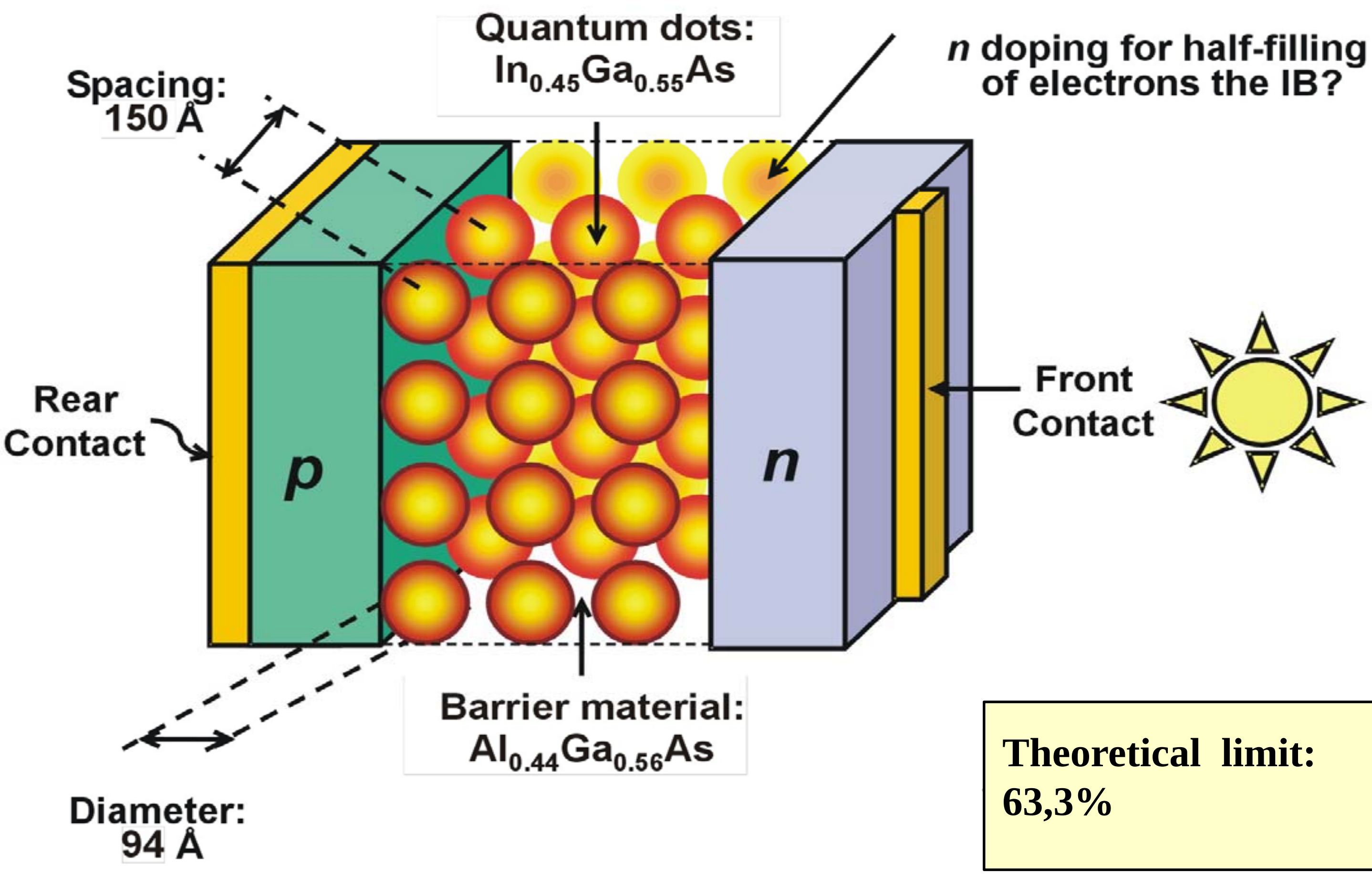
Theoretical limit: η=86,3%



Three junctions η=42%

High efficiency approach: Third generation solar cells (II)

- **Intermediate Band Solar Cell**



Theoretical limit: 63,3%

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Conclusions

•Silicon technology is dominating PV industry today

•Manufacturers choose the device structure reaching compromises between efficiency and fabrication cost

•With current technology, the energy invested in the fabrication of a PV system can be recovered in less than two years in South of Europe

•There are new concepts being explored which can significantly reduce the cost of the technology

•Photovoltaic solar energy will reach the competitive level in few years' time

Summary of PV technologies